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Kippes, Adam A.

Monterey, California. Naval Postgraduate School

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Characteristics of Upper-Level and Boundary
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by

Adam A. Kippes

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Characteristics of Upper-Level and Boundary Layer Forcing in Western Pacific Cyclones

by

Adam A. Kippes
Lieutenant Commander, United States Navy
B.S., University of Minnesota

Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN Meteorology and Physical Oceanography

from the

NAVAL POSTGRADUATE SCHOOL
September, 1991

ABSTRACT

A study of the characteristics of upper-level and boundary layer forcing in Western Pacific cyclones is conducted. Data for this study consists of twenty seven cyclones identified during the months of February and March 1986 and 1987. The cyclones were stratified into three separate classes of weak, moderate and intense cyclones based on observed deepening rates. Each class of cyclone was examined to determine general characteristics of the upper-level and boundary layer forcing. A representative cyclone from each class was chosen and a detailed examination of the upper-level and boundary layer forcing was conducted. Results indicate that during rapid deepening coupling between the upper-level forcing and forcing in boundary layer occurred only in the moderate and intense cases and was the result of strong baroclinic forcing aloft in these cyclones.

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I. INTRODUCTION

During the wintertime, cyclogenesis occurs frequently over the Yellow Sea and East China Sea. Cold air outbreaks from the mainland of China sweep south interacting with the warm waters of the western boundary current forming a surface baroclinic zone favorable for cyclonic development. The majority of these developing cyclones move northeastward following the maximum sea surface temperature gradient associated with the Kuroshio current. Some of these cyclones deepen rapidly over a short period of time and produce severe weather which poses a serious threat to the populous areas of Japan and coastal China. Sanders and Gyakum (1980) termed these rapidly deepening cyclones "bombs" and defined them as a cyclone that exhibits a maxixmum 24-h pressure fall of at least 24-mb, when geostrophically adjusted to 60N.

Numerous climatological and case studies have attempted to identify the forcing mechanisms responsible for rapid cyclogenesis, which includes upper-level baroclinic processes, air-sea interaction processes and diabatic heating processes. The significance of any single process to the cyclogenesis varies from case to case and the prevailing thinking, as summarized by Uccellini (1990) suggests that it is several processes working in concert that leads to rapid development. Critical to understanding rapid cyclogenesis then is our

understanding of how these individual processes combine over the spectrum of cyclones. Consequently, the major thrust of the present study is to identify common features of both strong and weak cyclones in order to better understand how the various processes combine in the most intense cases.

A. BACKGROUND

In the past decade, numerous case studies have focused on the analysis of the upper-air mechanisms responsible for cyclonic development. Strong cyclonic vorticity advection aloft is the primary upper-level process responsible for surface cyclogenesis. Chen and Dell'Osso (1987), in a case study of East Asian cyclogenesis, examined the role of cyclonic vorticity advection and determined that a mid-tropospheric short-wave trough upstream from the surface trough, was the key forcing mechanism aloft. As this upper-level feature approached an already established surface inverted trough, rapid cyclonic spin-up occurred at the surface. Bosart (1981) and Uccellini et al (1984) also found that rapid cyclonic spin-up at the surface was associated with the approach of a strong 500-mb short wave trough in this study of the coastal Presidents' Day storm of 1979. These results were generalized in a climatological study by Sanders (1986), which showed that the strength of the 500-mb vorticity advection correlated with the intensity of the subsequent cyclogenesis.

Jet streaks as an upper-level forcing mechanism was examined by Uccellini and Kocin (1987) in their work with heavy snowfall events along the East coast of the United States. They showed that the positioning of the jet streaks and their associated vertical circulations provide a link between the upper-level troughs, jet streaks and the surface cyclone. Uccellini et al. (1987) found similar results utilizing numerical model studies of the February 1979 Presidents' Day storm. They showed that jet streak positioning and the associated transverse vertical circulations lead to the development of a low-level jet (LLJ) that enhanced secondary cyclogenesis which was necessary for rapid development in that case. Studies by Reed and Albright (1986), Wash et al. (1988) and others also suggest that the upper-level divergence produced by jet streaks can force rapid cyclogenesis even in the absence of a significant 500-mb trough.

Surface heat and moisture fluxes within the PBL and surface layer are the primary surface processes that contribute to rapid cyclogenesis. While generally accepted that these processes can be a significant forcing mechanism in cyclonic development, the degree to which they contribute is unclear. Atlas (1987) demonstrated that the role of surface heat fluxes in cyclonic development was to reduce static stability, increase cyclonic vorticity and increase baroclinicity in the vicinity of cyclonic activity.

The release of latent heat release in the mid-troposphere is also a contributing process to rapid cyclogenesis. Uccellini et al (1987) linked surface heat and moisture fluxes within the oceanic PBL to mid-tropospheric latent heat release. In controlled simulations, they determined that the role of the fluxes was to reduce static stability providing a more conducive environment for cyclonic growth. Additionally, these heat and moisture fluxes combined with jet streak related transverse circulations to enhance mid-troposheric latent heat release. Further evidence of the interaction between latent heat release and surface heat fluxes was provided by Chen and Dell'Osso (1987). In a numerical case study of East Asian cyclogenesis, simulated model runs were conducted with surface heat fluxes and without surface heat fluxes. The absence of sensible heating resulted in a decrease in the latent heat release, which indicates that surface sensible heating is important in cyclonic development in so far as it contributes to the latent heat release. Similar numerical model experiments by Anthes et al. (1983), Chen et al. (1983) and others demonstrate the importance of latent heat release to rapid cyclogenesis.

While much of the work cited in the preceeding paragraph deals strickly with coastal cyclogenesis, the role of boundary layer fluxes in developing oceanic systems is still under investigation. Recent studies suggest that the distribution of the fluxes in relation to the developing cyclone may be

important. Reed and Albright (1986) suggested that positive heat fluxes to the northeast of a surface low was instrumental to rapid development. Recent work by Nuss and Kamikawa (1990) linked upper-level forcing in the form jet induced transverse circulations with processes acting in the PBL. In a study of two East Asian cyclones, they concluded that a strong ageostrophic vertical circulation was instrumental in sustaining strong positive surface fluxes in the vicinity of the updraft region of an intense cyclone. The presence of these surface fluxes served to raise the boundary layer equivalent potential temperature in a region of moist symmetric instability contributing to the explosive development. Nuss (1989) showed that patterns of surface heating that resulted in unstable PBL conditions to the northeast of the warm front and stable PBL stratification to the south enhanced cyclonic development. The presence of upward heat fluxes northeast of the surface low destabilize the PBL and increase the frictional convergence into the surface cyclone and along the warm front resulting in an increased transport of heat and moisture out of the boundary layer. The result is stronger mid-tropospheric heating and increased cyclonic intensity. The previous studies discussed above establish both the role of individual processes as well as the coupling between them for rapid cyclogenesis. This thesis examines a number of oceanic cyclones that developed in

the Western Pacific during the winter seasons of 1986 and 1987. The aim of this thesis is to:

1. Examine the characteristics of the upper-level forcing and jet-induced transverse circulations and their ability to couple with boundary layer forcing.

2. Determine whether coupled jet-induced transverse circulations and the boundary layer forcing are strictly characteristic of intense cyclones.

3. Examine the distribution and time evolution of surface fluxes in the PBL to identify the conditions favorable for enhanced cyclogenesis.

II. DATA

A. DATA BASE

Extratropical cyclones in the region 120E-160E and 20N-50N were tabulated on a daily basis for the months February and March 1986 and 1987 using gridded National Meteorlogical Center (NMC) final analyses. The NMC final gridded analyses are global analyses on 2.5 degree X 2.5 degree grid for 12 pressure levels from the surface to 50-mb. No modification to the analyses was done, although they were interpolated to an 80 km Lambert conformal grid for display and diagnostic computation.

B. DATA STRATIFICATION

The cyclone events were stratified by examining the central pressure deepening rates. A total of twenty seven cyclones were identified. The total central pressure fall over the life of the low per the number of hours of actual deepening was determined from the gridded pressure analyses. For a low to be counted, one closed isobar had to have persisted for at least 24-h. The pressure fall in mb/h was calculated from the pressure obtained from the NMC grids. The storms were stratified following the approach of Sanders (1986), which used a deepening rate expressed in Bergerons (1 Bergeron = 24-mb/24-h ($\sin \phi$ / $\sin 60$)). The latitude of each

low at the midpoint of the 24-h period of most rapid deepening was determined and the deepening rate in Bergerons was calculated in Table 1. The following three classes of intensity were identified: weak: less than 1.2 Bergerons; moderate: between 1.2 and 1.6 Bergerons; intense: greater than 1.6 Bergerons. All the cyclones in each class are listed in Table 1.

TABLE 1 DATES, DEEPENING RATES AND CLASSIFICATION OF WESTERN PACIFIC CYCLONES.

DATE	DEEPENING RATE (MB/HR)	BERGERONS	CLASSIFICATION
		1986	
8-9 Feb	0.5	0.8	Weak
11-12 Feb	1.2	1.8	Intense
14-16 Feb	0.6	1.1	Weak
17-21 Feb	0.5	1.3	Moderate
23-26 Feb			
Storm 1	0.3	0.4	Weak
Storm 2	0.7	1.0	Weak
27-28 Feb	0.8	1.5	Moderate
1-2 Mar	0.7	1.0	Weak
3-7 Mar	0.8	1.3	Moderate
9-12 Mar			
Storm 1	0.4	0.7	Weak
Storm 2	0.6	0.9	Weak
13-18 Mar	0.5	0.7	Weak
19-21 Mar	0.6	1.0	Weak
21-24 Mar	1.0	1.6	Intense
		1987	
1-6 Feb	0.9	1.5	Moderate
10-15 Feb	1.2	1.6	Intense
16-21 Feb	0.7	1.1	Weak
22-27 Feb			
Storm 1	0.8	1.3	Moderate
Storm 2	0.2	0.3	Weak
Storm 3	0.4	0.5	Weak
1-4 Mar	0.5	0.9	Weak
6-8 Mar	0.3	0.6	Weak
9-10 Mar	0.9	1.5	Moderate
10-12 Mar	0.3	0.9	Weak
13-17 Mar	0.6	0.9	Weak
19-21 Mar	0.3	0.4	Weak
23-25 Mar	1.0	1.9	Intense

III. WESTERN PACIFIC CYCLONE CHARACTERISTICS AND CASE STUDIES

A. 1 FEB - 31 MAR 1986

During the period 1 February 1986 to 24 March 1986, a total of fourteen cyclones developed in the vicinity of the East China Seas and surrounding regions, an average of 1 cyclonic event every four days. Eleven of the fourteen cyclones developed over water to the south and southeast of Japan. Tracks of all the cyclones are shown in Fig 1. These systems tracked northeastward following the main flow of the Kuroshio. With the exception of one case, maximum deepening took place along the axis of the Kuroshio. In all the cases, development was preceeded by strong northerly flow from mainland China over the area. This is in good agreement with the results of Hanson and Long (1985) and Gyakum et al. (1989) who found this area to be extremely favorable for cyclogenesis. Two of the three remaining lows developed over mainland China while one system developed over the Yellow Sea. The tracks of two of these cyclones was predominately eastward north of the maximum sea surface temperature (SST) of the Kurshio. The remaining cyclone tracked southeast across Japan into the Kuroshio before turning northeast.

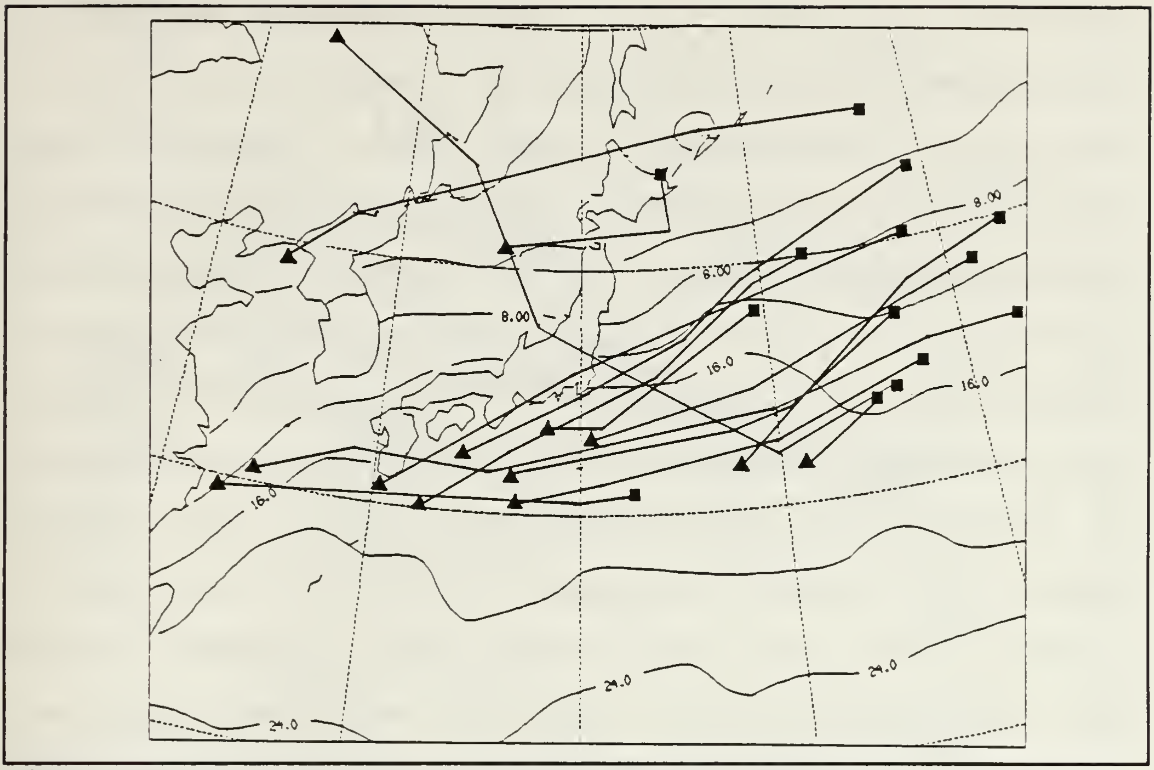

Figure 1. Cyclone tracks for February and March 1986: Solid contours are sea-surface temperature (C).

B. 1 FEB - 31 MAR 1987

The pattern of cyclone development observed during February and March 1987 was similar to that seen during 1986 for the same time period. A total of thirteen cyclones were identified during period 1 February to 31 March 1987, an average of 1 cyclonic event every four days. Eight of the thirteen cylones developed over the East China sea and regions to the south and southeast of Japan. Tracks of all the cyclones are shown in Fig. 2. These systems tracked northeastward along the axis of the Kuroshio with maxixmum deepening occurring over the Kuroshio. This was consistent

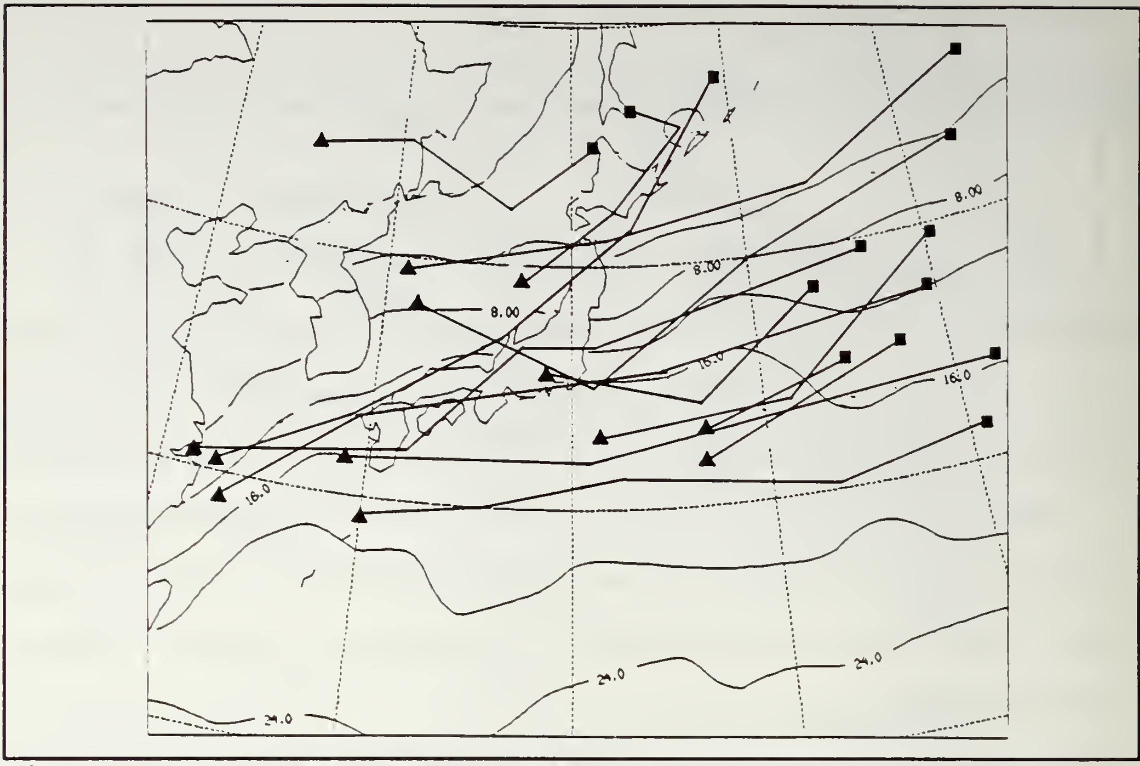

Figure 2. Cyclone tracks for February and March 1987: Same as Fig. 1.

with that observed during 1986 and with the results of Hanson and Long (1985) and Gyakum et al. (1989). Three of the remaining five cyclones developed over the Yellow Sea. Two of the cyclones tracked northeastward, one along the east coast of Japan and one north of the maximum gradient of the Kuroshio. The remaining cyclone tracked southeast across Japan before turning northeast and following the Kuroshio. The two remaining cyclones developed over land, one over the east coast of Japan which tracked northeastward over the Kuroshio and one over mainland China which tracked eastward north of the Yellow Sea.

C. CYCLONE CHARACTERISTICS

Cyclone characteristics were determined by examining the upper-level and boundary layer forcing present in the three cyclone classifications. Upper-level forcing was determined by examining the 300-mb isotach and sea-level pressure analyses to assess the low positions relative to the jet-streaks. In addition, 500-mb height and vorticity analyses were examined to define the vorticity advection associated with upper-level troughs. The 1000-mb temperature, sea-level pressure and surface wind vectors were examined to define the low-level thermal advection. These analyses were also used to identify the fronts associated with each storm. The boundary layer forcing was assessed by examining the air-sea temperature difference and surface heat and moisture flux analyses over the life cycle of each cyclone. These surface fluxes were computed using the PBL model of Brown and Liu (1982). Individual cases were selected to best illustrate the general characteristics of each classification in the following sections.

1. Weak Cyclones

a. General Characteristics

Of the twenty seven cyclones examined, seventeen were classified as weak with Bergeron values less than 1.2. Periods of maximum deepening were characterized by central pressure falls less than 20-mb/24-h.

These systems were characterized by weak upper-level forcing. Weak forcing is defined by a lack of organization in the forcing aloft. The cyclones were often positioned ahead of a low to medium amplitude 500-mb troughs. Vorticity maximums associated with these troughs were often less than 20 X 10^{-5}/s. At 300-mb, the cyclones were positioned in regions of convergence aloft associated with the left entrance/right exit regions of jet streaks. This positioning of the low in areas of weak positive vorticity advection and convergence aloft is unfavorable for cyclone intensification.

At the surface, ten of the weak cyclones were characterized by moderate to strong warm air advection (WAA) through the warm frontal region and across the frontal zone and north of the cyclone center with moderate to strong cold air advection (CAA) confined to regions west of the cyclones. The thermal advection pattern was determined by analysing plots of 1000-mb isotherms and surface wind vectors. Moderate to strong thermal advection was determined by the presence of large surface wind vectors perpendicular to the temperature gradient. The pattern of thermal advection for this weak cyclone resulted in large positive values of surface heat flux north and west of the cyclones and lower positive values of heat flux in the warm frontal region, a pattern that suggests a counteracting effect on the low-level baroclinicity in these cyclones. In these cases, warm fronts were difficult to identify and often absent. The seven remaining cyclones showed

weak to moderate CAA north and west of the cyclone center with strong to WAA through the warm frontal region. A similar pattern of surface heat flux distribution was observed with positive values of surface heat flux north and west of the cyclone and lower positive values of surface heat flux in the warm frontal region. Warm front positions were more discernable in these cyclones and were observed to remain stationary or advance slightly northward during the life cycle of the cyclone.

b. Case Analysis (17 Feb - 19 Feb 1987)

The case of 17-19 February 1987 illustrates the general characteristics of the weak cyclones. The system began as an 1015-mb inverted surface trough located over the East China Sea. The trough moved eastward deepened only 4-mb during the first twenty four hours, from 0000Z 17 February to 0000Z 18 February. Cyclogenesis was initiated as the trough moved over the Kuroshio. The next twenty four hours (0000Z 18 February to 0000Z 19 February) were characterized by modest deepening (17-mb) as the cyclone tracked northeastward along the Kuroshio.

(1) Pre-deepening Phase (00Z 17 - 00Z 18)

The first 24-h period or pre-deepening phase is characteristic of the lack of organized forcing aloft observed in most of the weak cyclones examined in this study. Fig. 3

shows the 500-mb heights and absolute vorticity at 1200Z 17 February, in the middle of the pre-cyclogenesis phase. The lack of significant troughing and the weak vorticity maxima persisted throughout the life of the cyclone. The cyclone is positioned south of Japan near 31N 132W at this time, which is

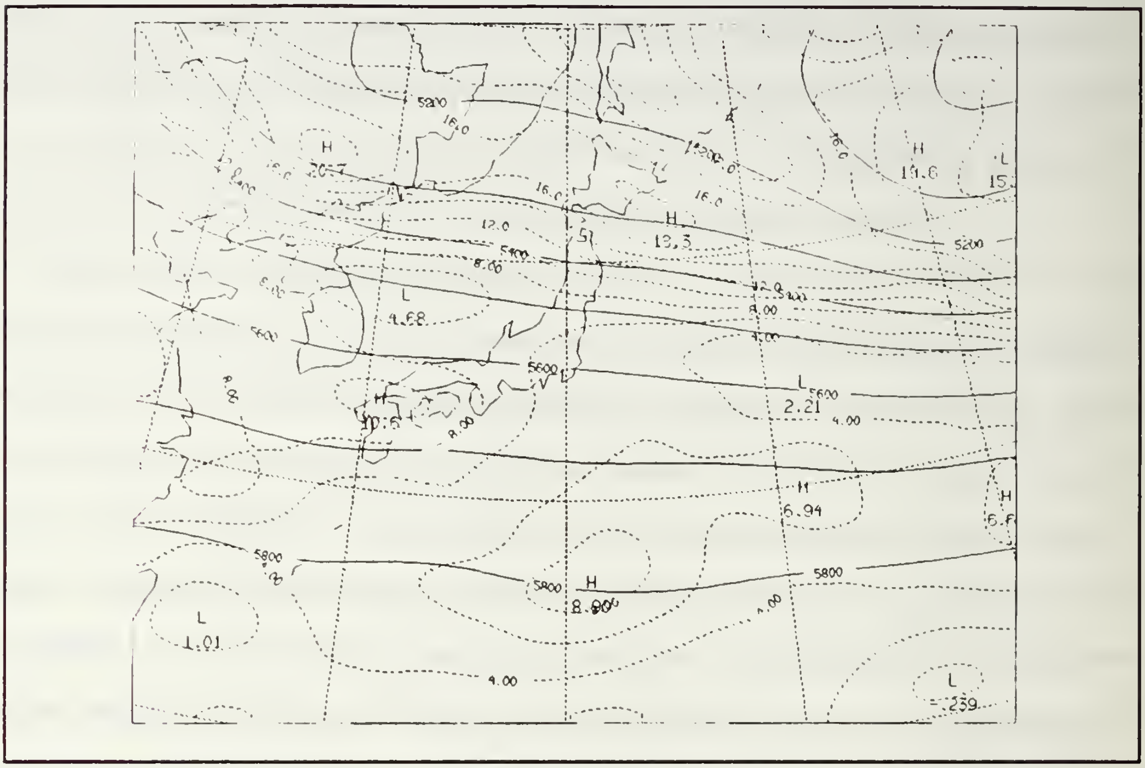

Figure 3. 1200Z UTC 17 February 1987 Upper-Level Analysis: NMC analysis of 500-mb heights, m (solid) and absolute Vorticity, 10^{-5}/s (dashed).

south of the primary jet as seen by the 300-mb isotachs in Fig. 4. A strong polar jet exists along 40N to the east of Japan and a much weaker sub-tropical jet (SJT) (at 300-mb) exists south of Japan along 30N. The STJ has its maximum wind above this level at 250-mb.

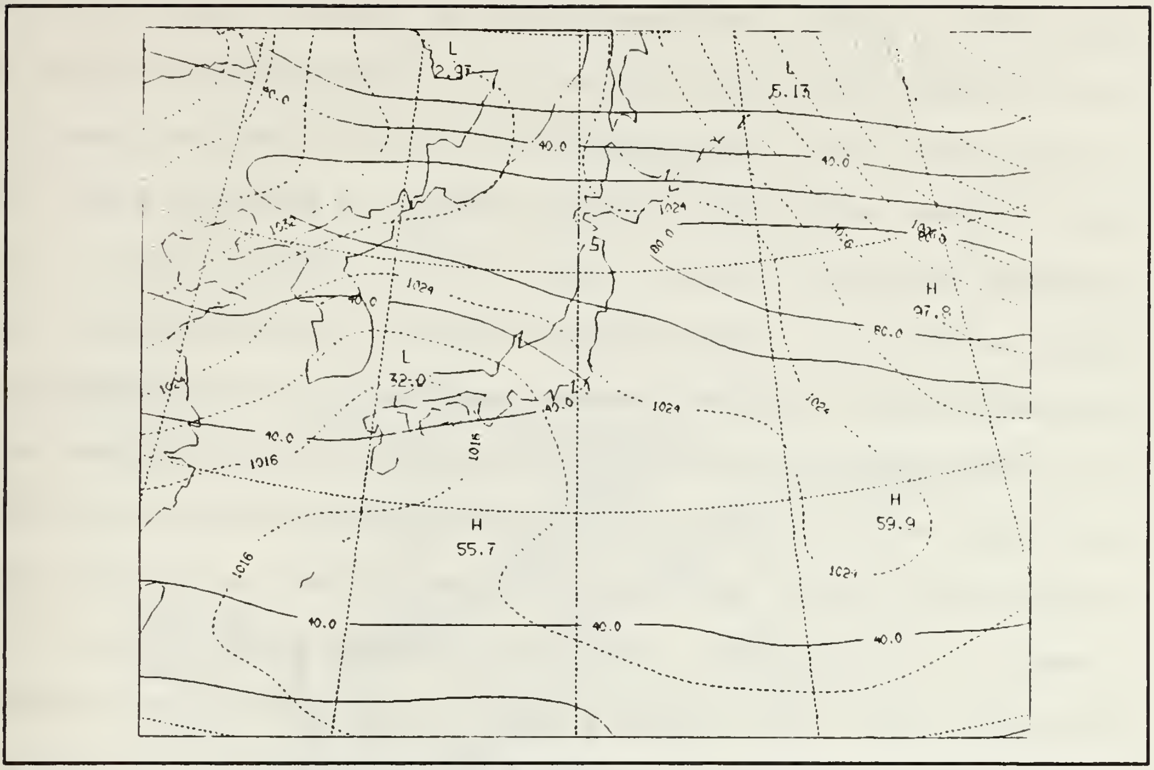

Figure 4. 1200Z UTC 17 February 1987 Upper-Level Analysis: NMC analysis of 300-mb isotachs, m/s (solid) and 1000-mb surface pressure, mb (dashed).

The surface low is positioned in the left entrance region of a 55 m/s (at 300-mb) jet streak in the sub-tropical jet, which is an unfavorable position for development as convergence is expected aloft. The position of this cyclone north of the sub-tropical jet and south of the polar jet was observed to occur in the majority of the weak systems.

The low-level structure of the developing cyclone at 1200Z 17 February is more favorable for intensification. Moderate to strong CAA north and northwest of the trough and moderate WAA advection east of the trough in the warm frontal region supports surface cyclogenesis. The warm front (not shown) is

positioned along the west coast of Japan. A plot of the surface heat flux distribution shows large positive values of surface heat flux are present to the north and northwest of the cyclone center with smaller values of positive heat flux present west and in the warm frontal region south of the cyclone (Fig. 5). This heating of the air to the west and east of the cyclone has a counteracting effect on cyclogenesis as the heating pattern tends to reduce baroclinicity across both the warm and cold fronts. The large positive values of surface heat flux located northeast of the cyclone along the east coast of Japan agrees with the pattern shown by Reed and Albright (1986) and others favorable for cyclonic development due to the reduction in static stability.

(2) Maxixmum Deepening Stage (00Z 18 - 00Z 19)

By 00Z 18 Feb, cyclogenesis was initiated and the 1011-mb low is positioned near 35N 139E (not shown). The upper-level forcing remains weak at 1200Z 18 February as suggested by the position of the 1006-mb cyclone in relation to the 300-mb jet pattern at the mid-point of maximum deepening (Fig 6). The low is positioned in an area of expected weak divergence aloft in the left exit region and right entrance region of two widely separated jet streaks.

At the surface, the cyclone has moved northeastward over the warmer water of the Kuroshio. The thermal advection pattern still favors further intensification. Moderate to

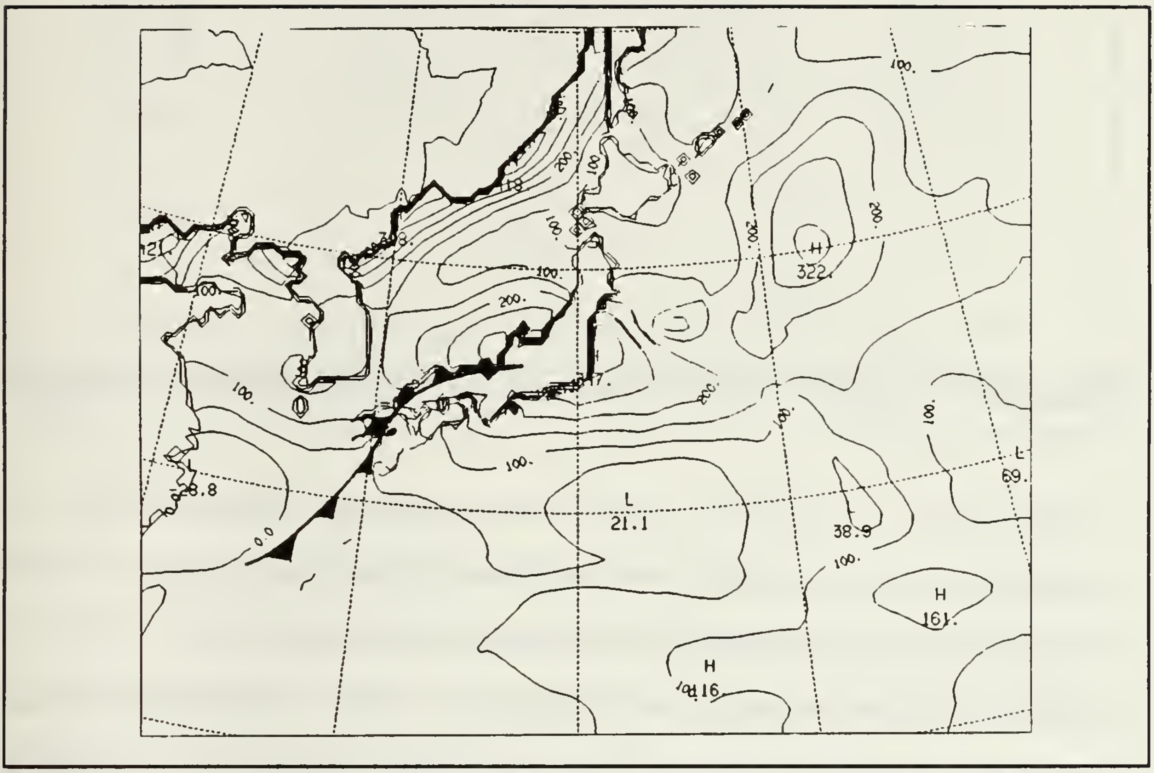

Figure 5. **1200Z UTC 17 February 1987 Surface Heat Flux Analysis:** in W/m^2. Position of low and fronts added.

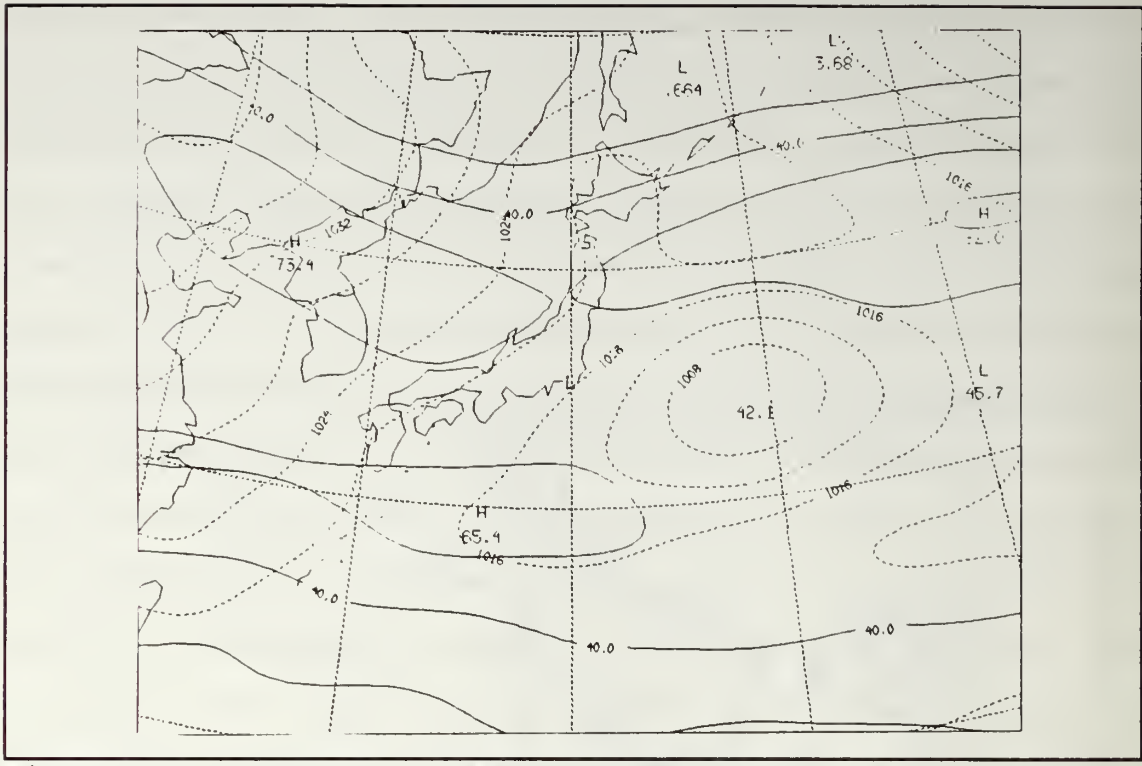

Figure 6. 1200Z UTC 18 February 1987 Upper-Level Analysis: Same as Fig 4.

strong CAA continues north and west of the cyclone with moderate to strong WAA east of the cyclone in the warm frontal region. Fig. (7) shows the surface heat flux distribution at time 1200Z 18 February and indicates that the movement of the cyclone over the Kuroshio has increased the surface heating to the west and north while low values of surface heat flux continue to the east of the cyclone. The warm front lies along a gradient of strong heating, which suggests considerable boundary layer instability north of the frontal zone as well as a tendency for weakening of the thermal gradient.

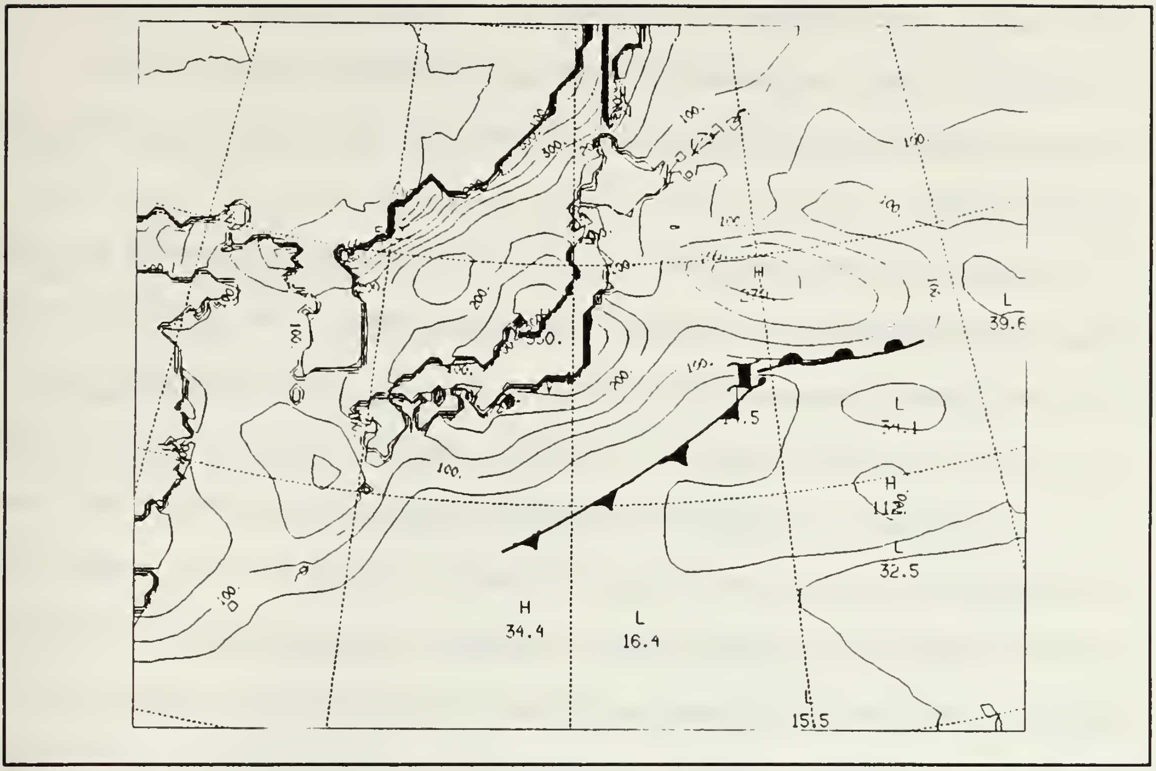

Figure 7. 1200Z UTC 18 February 1987 Surface Heat Flux Analysis: Same as Fig. 5.

2. Moderate Cyclones

a. General Characteristics

Six cyclones were classified moderate with Bergeron values between 1.2 and 1.5. All five displayed deepening rates greater that 20-mb/24-h.

Unlike the weak cyclones, upper-level forcing was stronger and more organized, which enhanced rather than opposed cyclogenesis in these moderate cases. Medium to high amplitude waves at 500-mb with strong vorticity maximums that equalled or exceeded 20 X 10^{-5}/s were characteristic of these systems during the period of maximum deepening. The surface lows were

favorably positioned in areas of 500-mb positive vorticity advection and expected 300-mb divergence associated with upper-level jet streak features during the periods of maximum deepening.

The low-level surface structure of these moderate systems was more favorable for cyclonic development than that observed in the weak cyclones. Moderate to strong CAA north and west of cyclone and moderate to strong WAA east of the cyclone characterized the thermal advection pattern around these lows. In three of the cases the warm front could not be identified and in the remaining three cyclones the warm front showed a slight advance northward over the cyclone life cycle. In all but one of the cyclones, the time evolution of low-level heating/cooling pattern was characterized by a increase in the heating of the surface layer north and west of the cyclone with increased cooling east and in the frontal zone over the life cycle of the storm. This pattern suggests an overall decrease in the low-level baroclinicity of the cyclones, however, it will be shown in the analysis of an individual case that this stabilization of the boundary layer south and destabilization of the boundary layer north of the cyclone was favorable for increased cyclonic development as cited by Nuss (1989).

b. Case Analysis (17 Feb - 21 Feb 1986)

This system began as 1012-mb low located over the East China Sea. The track of this cyclone was similar to the weak case. The low tracked east over southern Japan to near 32N 135W deepening 8-mb over the 24-h pre-deepening period (12Z 17 Feb - 12Z 18 Feb 1986). Once over the Kuroshio, the system moved northeast deepening 22-mb over the final 24-h period of maximum deepening (12Z 18 Feb to 12Z 19 Feb).

(1) Pre-deepening Phase (12Z 17 - 12Z 18)

This pre-deepening phase was characteristic of most of the moderate cyclone developments. Strong cyclonic vorticity advection at 500-mb is evident at 0000Z 18 February. Figs. 8 and 9, respectively, show the 500-mb and 300-mb patterns in place at the mid-point of this pre-deepening phase. The medium amplitude wave at 500-mb and associated 14 X 10^{-5}/s vorticity maximum lags the surface low and is in a favorable position to project positive vorticity advection over the surface feature. At 300-mb, a 60 m/s jet streak, just off the edge of the plot over mainland China, is positioned upstream from the cyclone and a 60 m/s jet streak is located downstream from the advancing cyclone. Although the low is not presently positioned under the right entrance region of this jet streak, it moves under the right entrance region by the beginning of its maximum deepening.

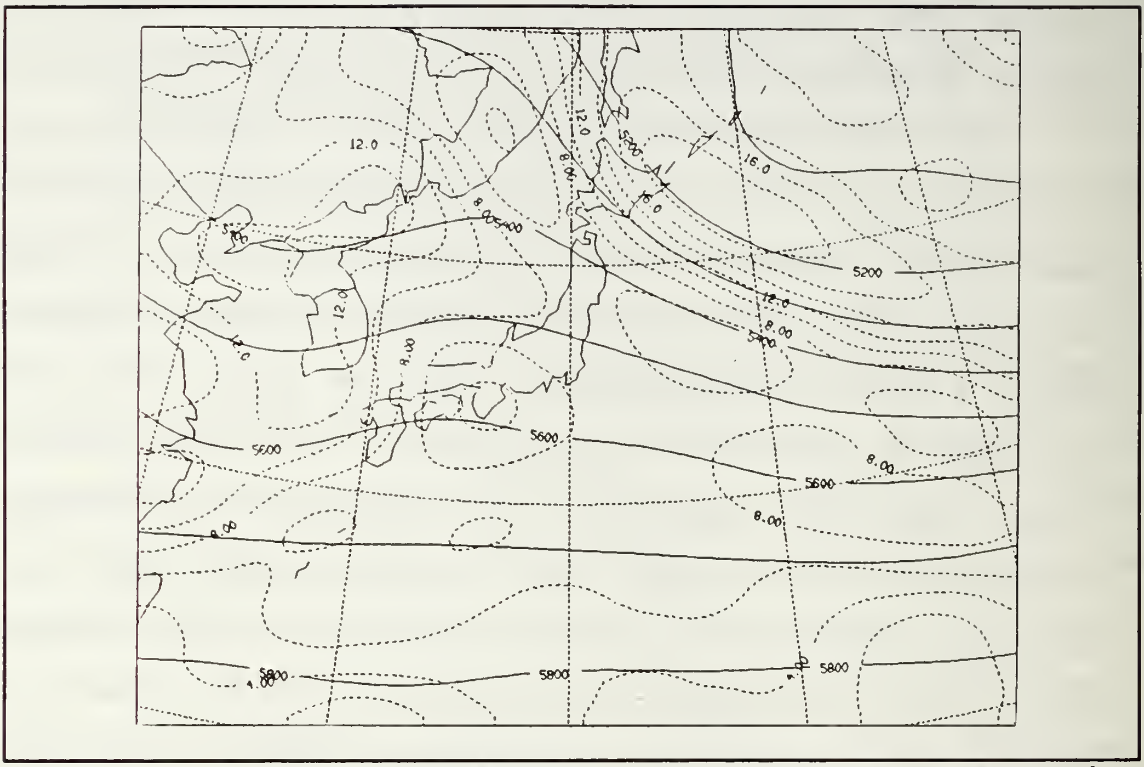

Figure 8. 0000Z UTC 18 February 1986 Upper-Level Analysis: Same as Fig. 3.

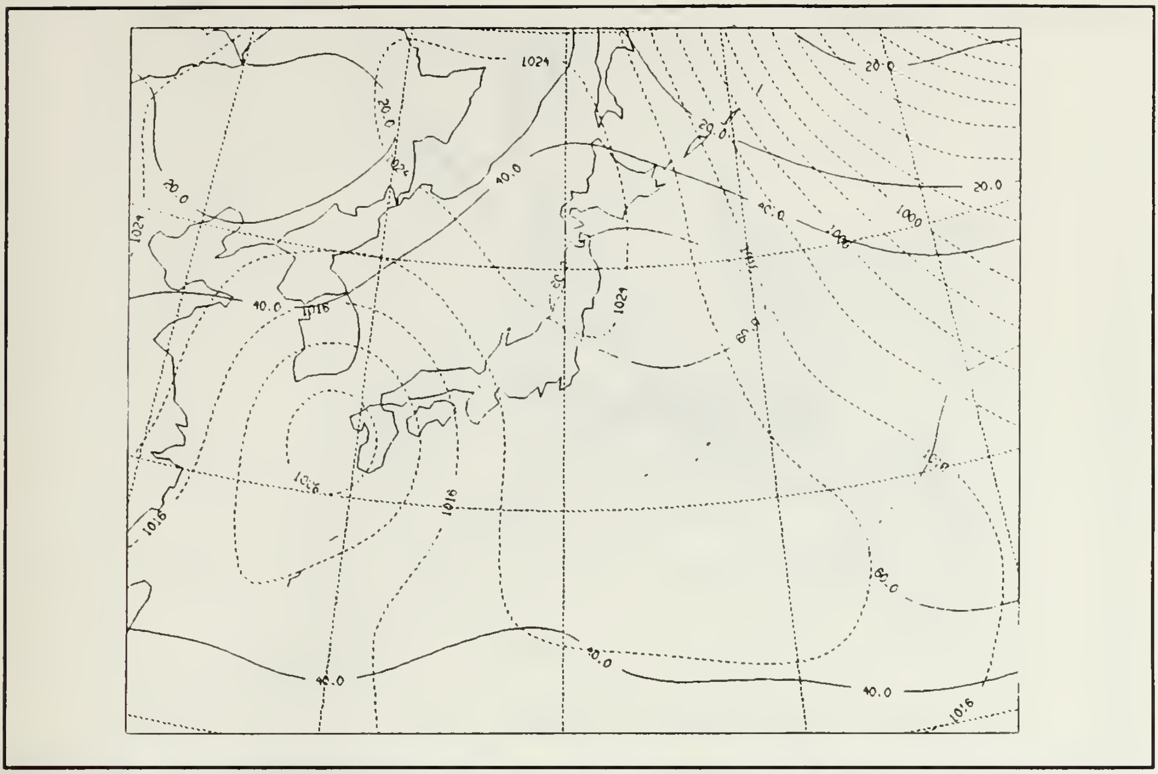

Figure 9. 0000Z UTC 18 February 1986 Upper-Level Analysis: Same as Fig. 4.

The thermal advection pattern around the surface low is well-established by 0000Z 18 February. Moderate CAA is taking place west of the cyclone while north of the cyclone, the easterly flow is resulting in little to no thermal advection. Moderate to strong WAA advection is taking place east of the cyclone. The warm front extends eastward across southern Korea to the west coast of Japan. An analysis of the surface heat distribution for this time period reveals low positive values of surface heat flux south of the cyclone center with larger positive values west and through the warm frontal zone extending north of the cyclone (Fig. 10). This pattern of strong warming of the cold air to the west and within the warm

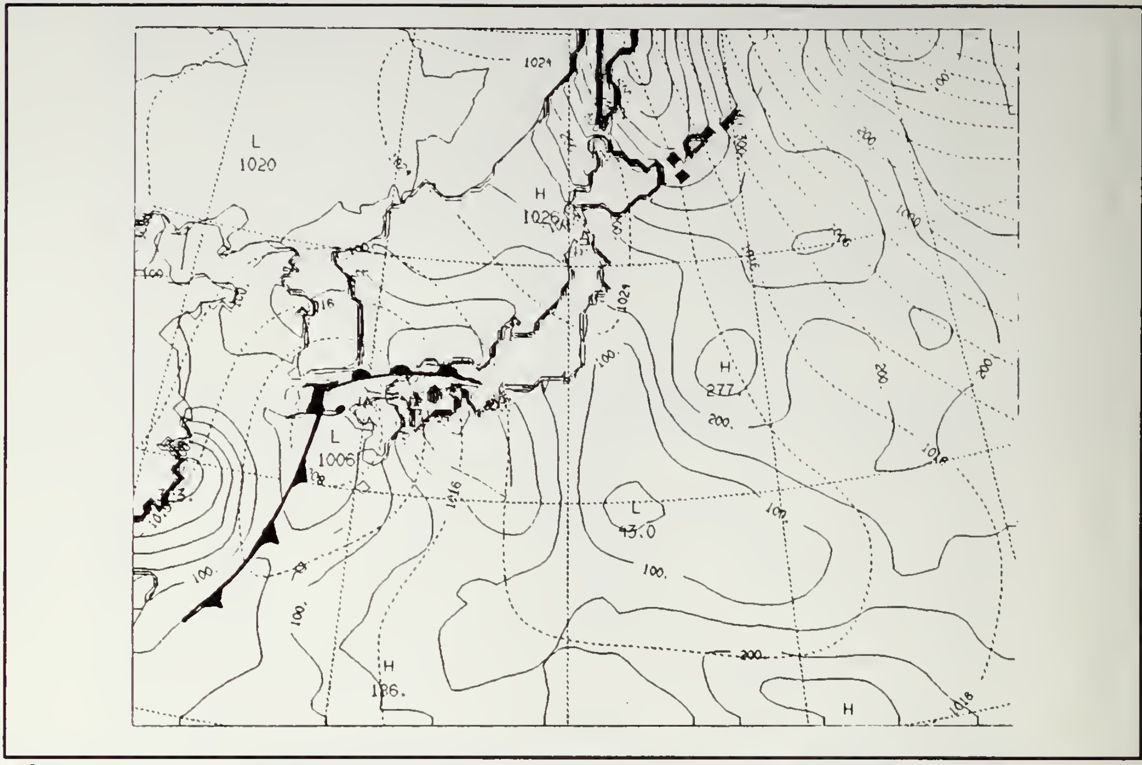

Figure 10. 0000Z UTC 18 February 1986 Surface Heat Flux Analysis: Same as Fig. 5.

frontal region has a counteracting effect on the low-level baroclinicity of the cyclone.

(2) Maximum Deepening Phase (00Z 19 - 00Z 20)

The upper-level forcing at 500-mb remains strong and well established during this maximum deepening phase as would be expected for intense cyclogenesis. The 500-mb trough has advanced eastward to just east of Japan and amplified as shown in Fig. (11). The vorticity maximum has increased to 20 X 10^{-5}/s. The surface cyclone remains ahead of this advancing wave in a region of strong positive vorticity advection. At 300-mb, a 80 m/s jet streak is now located south

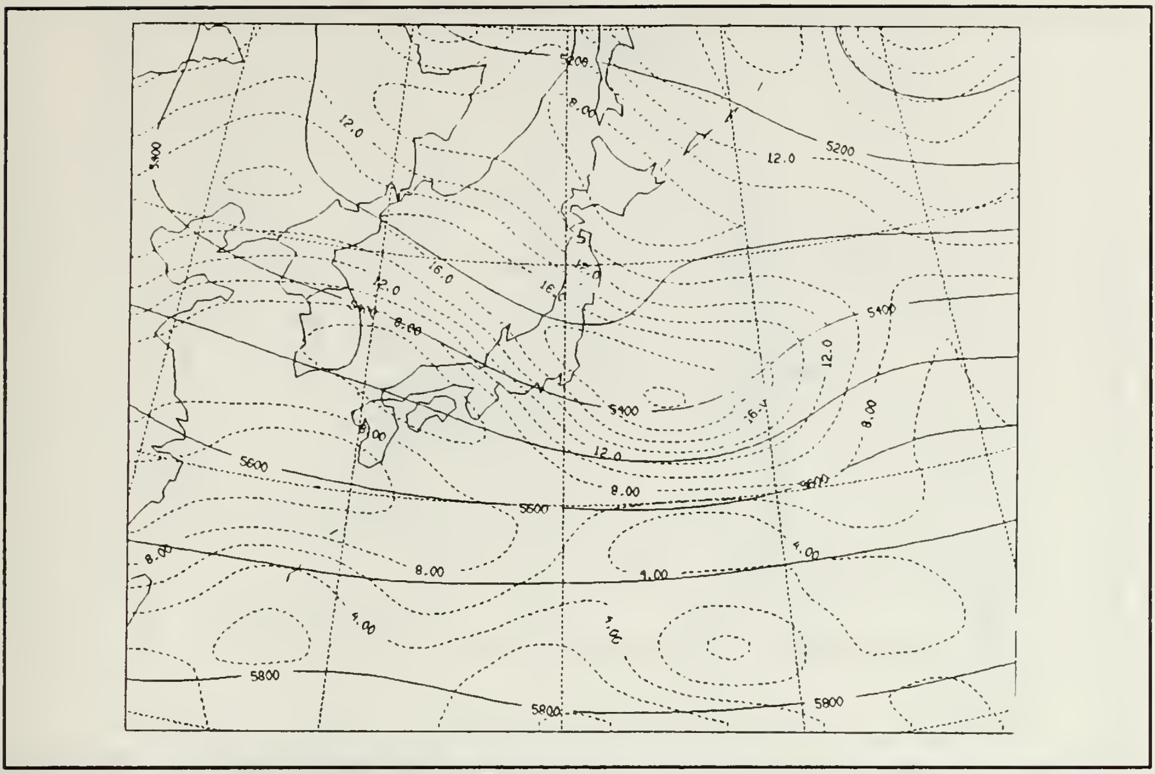

Figure 11. 1200Z UTC 19 February 1986 Upper-Level Analysis: Same as Fig. 3.

of Japan to the southwest of the surface low. Fig. (12) shows that the cyclone is positioned near the left exit region of the jet streak in an area of probable divergence aloft, which is consistent with the vorticity advection pattern at 500-mb.

Similar to the weak case, the track of the moderate cyclone takes it over the Kuroshio during the maximum deepening phase. Moderate to strong CAA is occurring to the northwest and west of the cyclone with moderate to strong WAA occurring to the southeast of the cyclone. This observed thermal advection pattern favors continued intensification of the low as expected during this deepening phase.

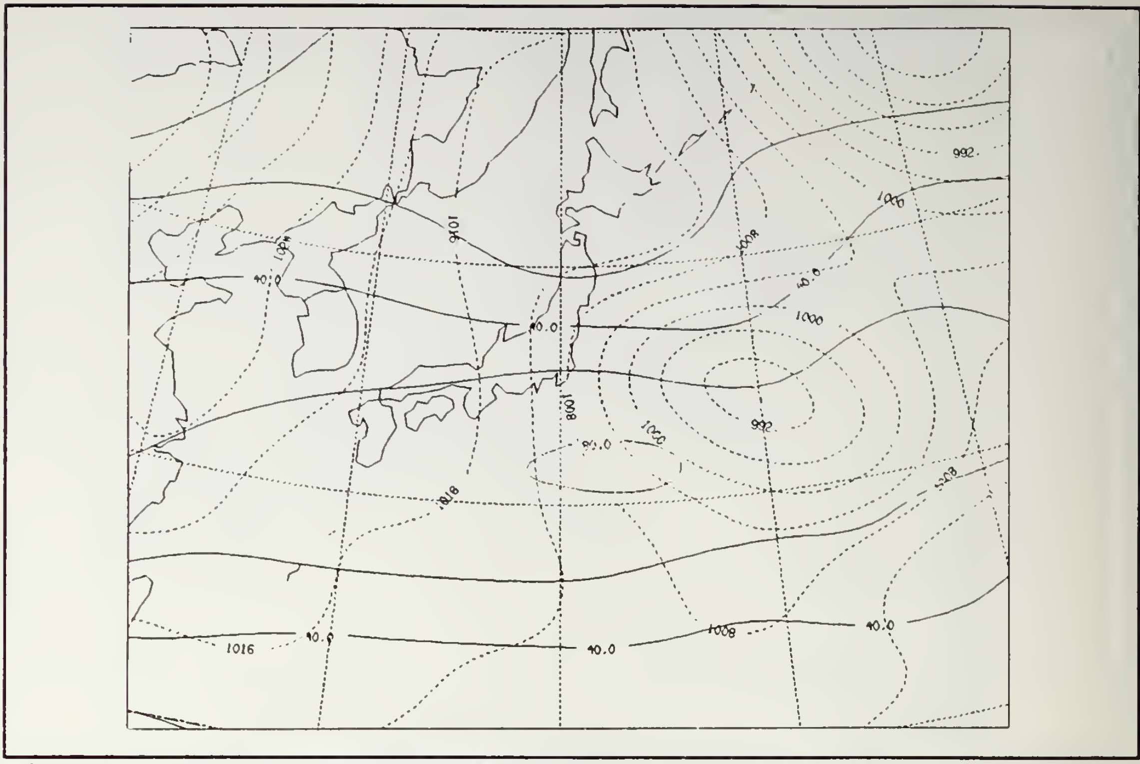

Figure 12. 1200Z UTC 19 February 1986 Upper-Level Analysis: Same as Fig. 4.

The low-level heating and cooling pattern is significantly different from that observed 24-h earlier. Smaller positive values of surface heat flux are present to the west of the cyclone with larger positive values of surface heat flux east of the cyclone in the warm frontal region (Fig. 13). Negative values of surface heat flux (cooling) are present south of the low along the position of a trailing cold front. This pattern suggests that the thermal gradient along the cold front is changing very little or being increased by the heating pattern, while the warm front is being weakened. The warm front lies along 35N in region of surface heating. Large positive values of surface heat flux are present to the north

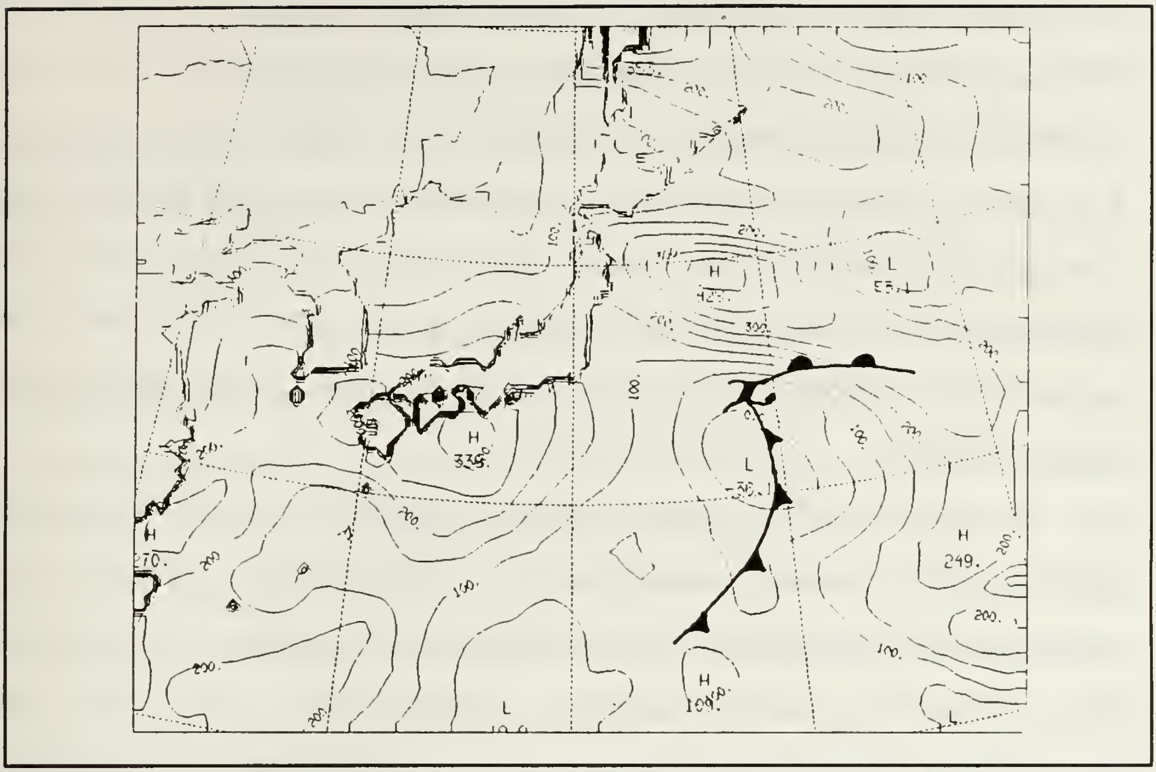

Figure 13. 1200Z UTC 19 February 1986 Surface Heat Flux Analysis: Same as Fig. 5.

and northeast of the cyclone, a condition suggested by Nuss (1989) and others as significant to enhanced cyclogenesis.

3. Intense Cyclones

a. General Characteristics

Four of the twenty seven cyclones were classified as intense. These systems were unique in that they experienced central pressure falls of at least 24-mb/24-h. The general charateristics common to the intense cyclones were similar to those seen in the moderate case. The upper-level forcing was strong and well-organized. During the explosive phase of their development, half of the intense systems examined were

positioned between the exit and entrance regions of 300-mb jet streaks. This condition has been cited by Uccellini and Kocin (1987) as a characteristic of explosive systems. Additionally, all these systems were positioned ahead of a high amplititude trough at 500-mb in a region of strong positive vorticity advection. As seen in the moderate case, vorticity maximums equalled or exceeded 20 X 10^{-5}/s at the time of maximum deepening.

At the surface, these intense systems showed a similar pattern of thermal advection as the moderate cases, with moderate to strong CAA north and west with moderate to strong WAA in the warm frontal region. Warm frontal positions were easily identified and showed a general northward advance over time. All but one of these cyclones showed a flux pattern that would decrease the low-level baroclinicity over the life cycle of the cyclone. The surface heat flux distribution showed a steady decrease in positive values through the warm frontal region extending northward with increasing positive values of surface heat flux occurring in cold air to the west and north of the cyclone. As dicussed in the moderate case, this pattern has been shown in other studies to be favorable for rapid intensification.

b. Case Analysis (00Z 11 Feb - 00Z 12 Feb 1986)

The cyclone developed from a 1014-mb low located southeast of Japan. The cyclone tracked northeast along the Kuroshio deepening 28-mb over the 24-h period.

(1) Pre-deepening Phase (00Z 11 February)

The 12-h period prior to maxixmum deepening is characterized by favorable 500-mb but less favorable 300-mb patterns. At 500-mb, a high amplitude trough with a 22 X 10^{-5}/s vorticity maximum is positioned over southern Japan while at 300-mb, a 80 m/s jet streak is located south of Japan extending eastward along 30N (Figs. 14 and 15). A weak 1014-mb low is located southeast of Japan in a region of strong positive vorticity advection ahead of the upper-level trough but in a region of apparent convergence aloft in the left entrance region of the 80 m/s jet streak to the south.

The thermal advection pattern at 0000 11 February supports further intensification of the system. Strong CAA is occurring west of the cyclone with weak to moderate CAA north of the cyclone center. Moderate WAA is occurring east of the cyclone. Fig. (16) shows the distribution of surface heat flux during the pre-deepening phase. The location of the low, along the east coast of Japan, positions the center in a region of strong surface heating. The warm front extends eastward along 34N through a region of moderate surface heating. Large positive values of surface heat flux are present to the west

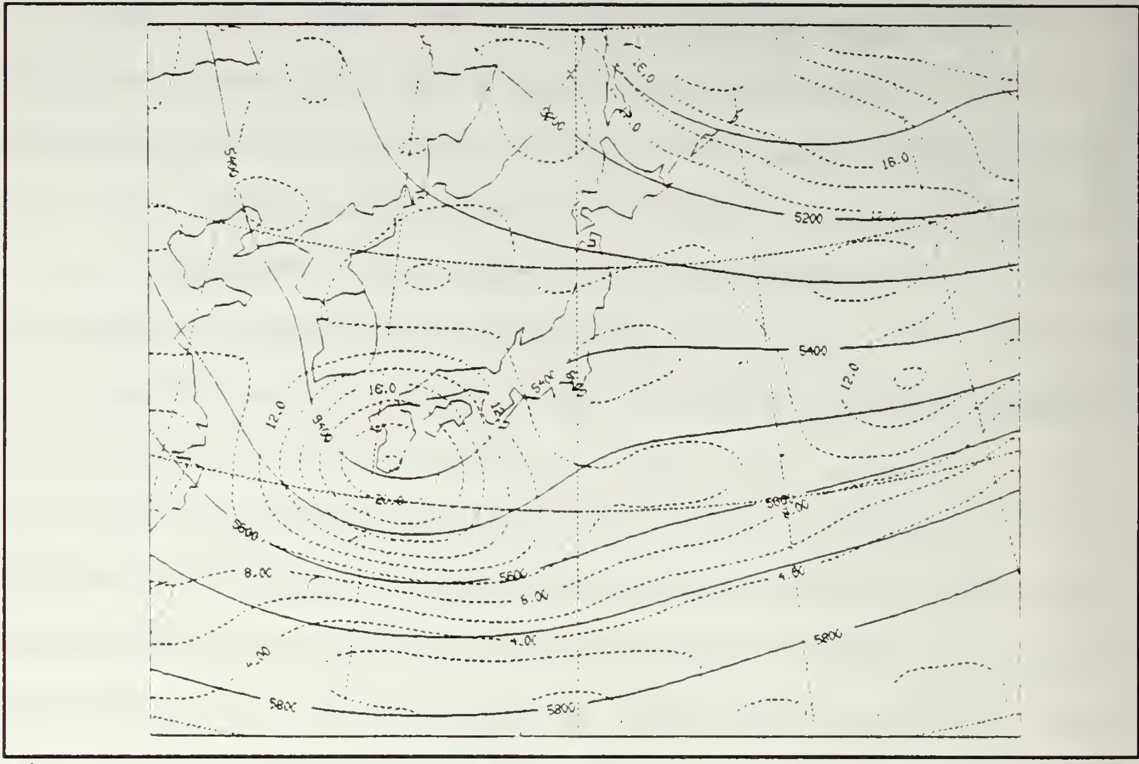

Figure 14. 0000Z UTC 11 February 1986 Upper-Level Analysis: Same as Fig. 3.

and north of the cyclone with smaller positive values of surface heat fluxin the warm frontal region. As indicated for the predeepening phase of the moderate case, dynamically, this pattern would reduce the baroclinic strength of the system.

(2) Maximum Deepening Phase (12Z 11 - 00Z 12)

The forcing aloft for this maximum deepening period is similar to that observed in the moderate case. At 0000Z 11 February, a high amplitude trough (Fig. 14) is present over southern Japan, which was just upstream of a 1000-mb surface low. Fig. 17 shows the position of the trough and associated 20 X 10^{-5}/s vorticity maximum relative to the

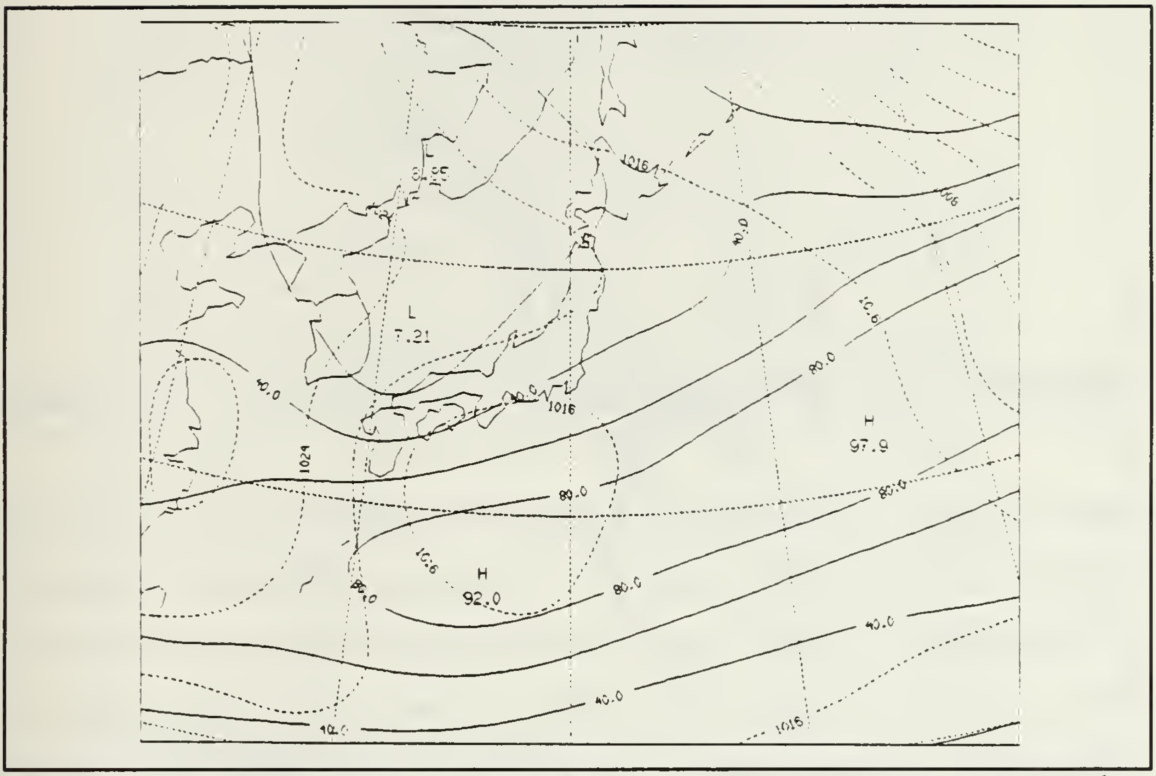

Figure 15. 0000Z UTC 11 February 1986 Upper-Level Analysis: Same as Fig. 4.

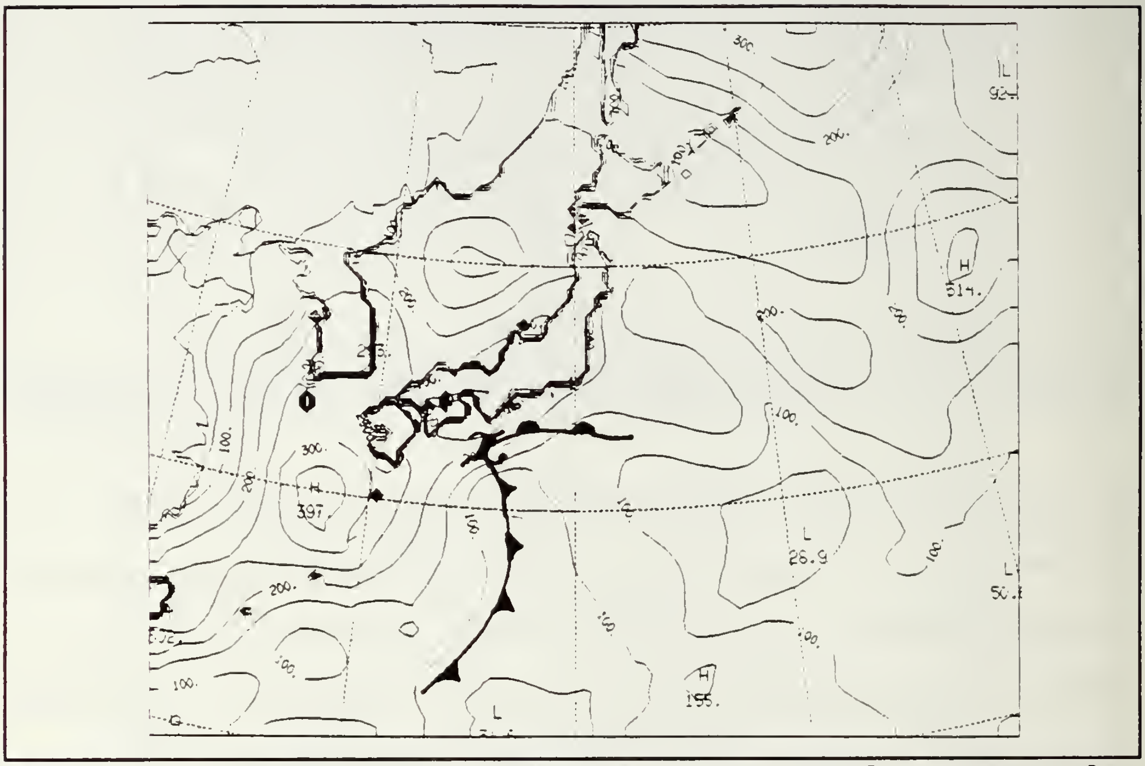

Figure 16. 0000Z UTC 11 February 1986 Surface Heat Flux Analysis: Same as Fig. 5.

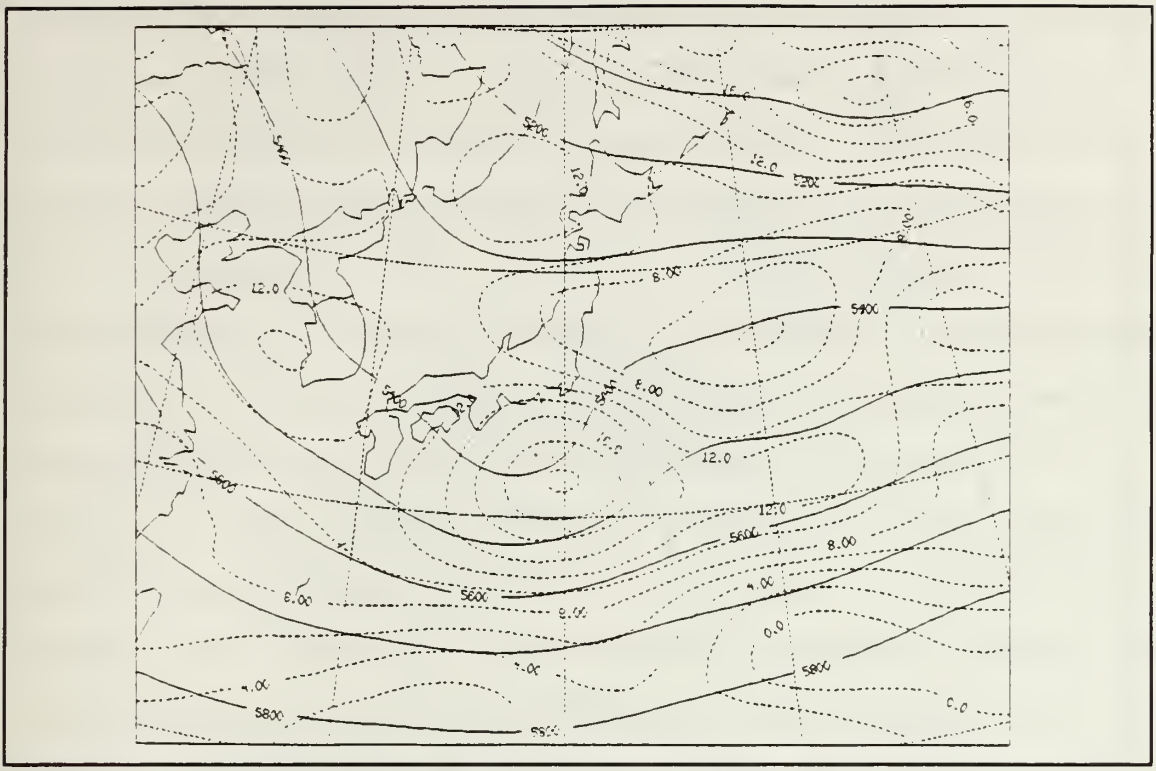

Figure 17. 1200Z UTC 11 February 1986 Upper-Level Analysis: Same as Fig. 3.

surface low at 1200Z 11 February. The cyclone, having already deepened 16-mbis located in a region of strong positive vorticity advection ahead of the advancing wave. At 0000Z 11 February, the cyclone is poorly positioned relative to the forcing at 300-mb. An 80 m/s STJ streak (Fig. 15) is located south of the developing low. The cyclone is positioned in the left entrance region of this jet streak in an area of convergence aloft for straight flow. By mid-period, at 1200Z 11 February, the 300-mb isotach analysis (Fig. 18) shows the elongated 80 m/s jet streak preparing to seperate into two jet streaks. The cyclone is located between the apparent separation point which is an area of convergence aloft for a

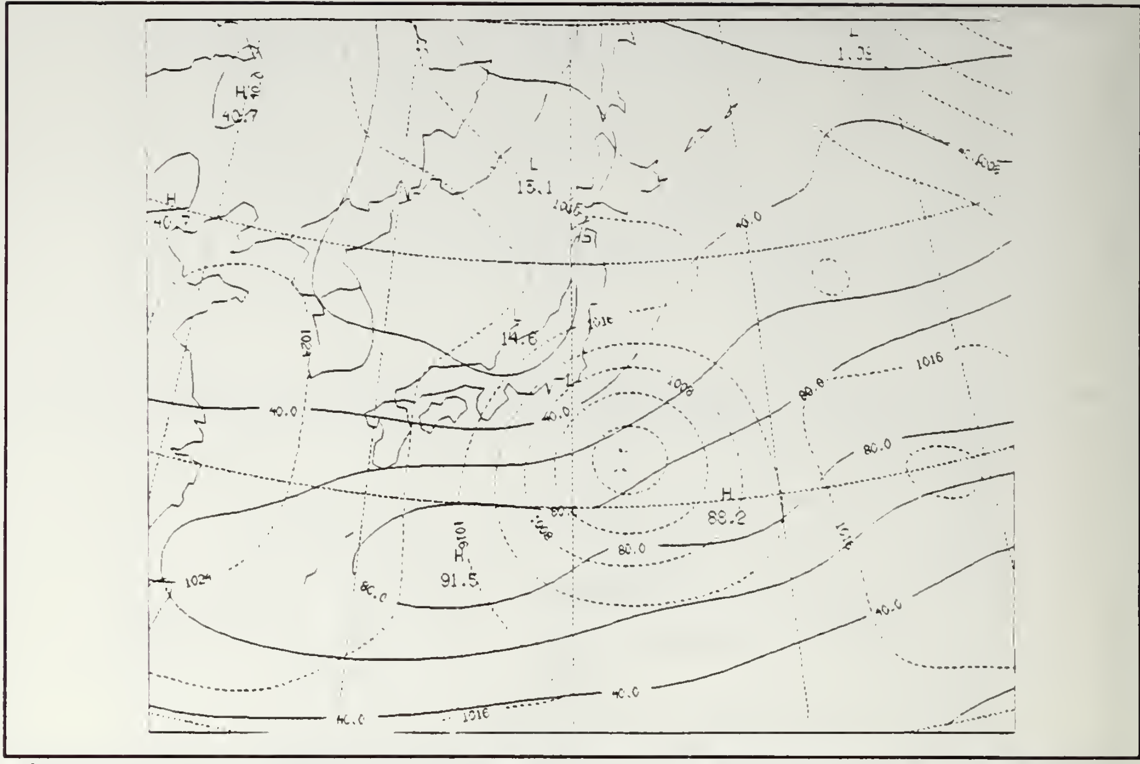

Figure 18. 1200Z UTC 11 February 1986 Upper-Level Analysis: Same as Fig. 4.

straight jet. However, an analysis of the divergence at 300-mb (not shown) at 1200 11 February indicated strong divergence over the cyclone position, which is evidently due to diffluence and curvature effects on the jet. Examination of 300-mb isotach analysis 12-h later confirms that two seperate 80 m/s jet streaks developed with the cyclone between the right entrance and left exit regions of the two jets, which is highly favorable for the rapid cyclogenesis.

This cyclone, like the weak and moderate systems, tracks northeastward over the Kuroshio during its maximum deepening. The pattern of thermal advection observed at the surface at 1200Z 11 February shows moderate CAA north of the cyclone

center with strong CAA occurring to the west. Like the moderate case, there is a strong southeasterly component to the WAA through the warm frontal region. The warm front extends eastward along 35N and has drifted slightly south over the 12-h period. This advection pattern favors further intensification of the cyclone. The pattern of heating and cooling at 1200Z 11 February shows a significant increase in the surface heating north and northeast of the cyclone (Fig. 19). The surface heat flux distribution has remained relatively constant to the west and through the warm frontal region with significant heating still present around the cyclone center and in the vicinity of the frontal zone. The overall pattern of heating and cooling should favor further development of the cyclone and the presence of large positive values of surface heat flux north and northeast of the low presents a potentially significant environment for rapid development as previously discussed in the moderate case.

D. SUMMARY

The major difference between weak systems and those classified as moderate or intense was in the intensity and organization of the upper-level forcing as well as the intensity of surface heating around the low. In the moderate and intense cases, forcing at 500-mb and 300-mb tended to enhance development of the surface cyclone by creating areas of strong positive vorticity advection and apparent divergence

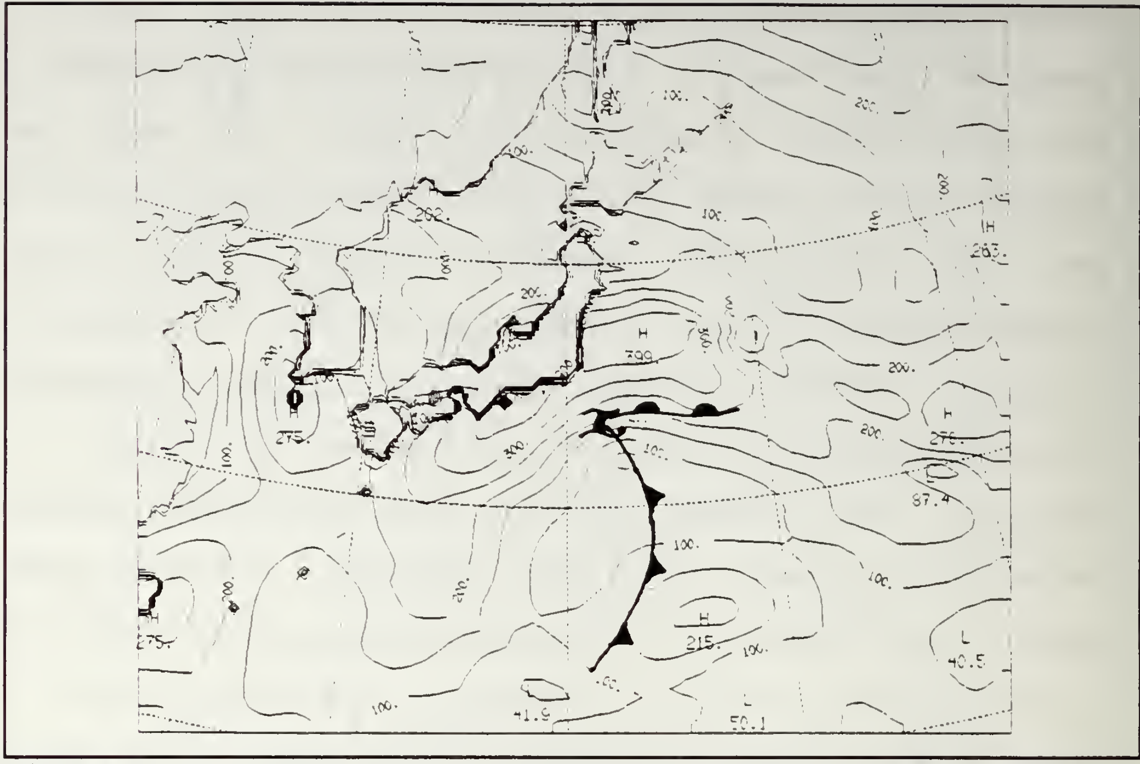

Figure 19. 1200Z UTC 11 February 1986 Surface Heat Flux Analysis: Same as Fig. 5.

aloft over the low. While in the weak case, the position of the surface low relative to the forcing at 500-mb and 300-mb was in areas of either weak positive vorticity advection or possible convergence aloft.

The distribution of surface heat flux north and west of the cyclone center was similar in all three classes. Large positive values of surface heat flux were present north and west of the cyclone, however, the magnitude of the heating was significantly greater in the moderate and intense cases and extended further east. The moderate and intense cases also showed stronger heating around the surface low and through the frontal region. This pattern provided a potentially more

explosive environment for rapid cyclogenesis in these systems as discussed earlier. Although not shown in the case study of the intense cylone, both the moderate and intense systems examined showed steadily decreasing positive values of surface heat flux through the warm frontal region. This implies an increase in the boundary layer stability through the warm frontal region during the later stages of the life cycle of the cyclone. This was not observed in the weak cyclones where stability through the warm frontal region remained the same or increased only slightly over the life cycle of the storm. The stabilization of the boundary layer through the warm frontal region and the presence of large positive surface heat fluxes north of the cyclone in the moderate and intense cases was cited by Nuss (1989) as potentially significant for enhanced development.

IV. COUPLING OF BOUNDARY LAYER AND UPPER-LEVEL PROCESSES

Wash et al. (1988) showed that rapid deepening occurred from the favorable position of a cyclone with respect to an upper-level jet streak. It was shown in the individual case analysis that the moderate and intense cyclones developed under more favorable upper-level forcing than the weak cyclone. Both the moderate and intense cyclones were positioned in areas of strong divergence aloft associated with 300-mb jet streaks. The effect of surface heat and moisture fluxes within the PBL on influencing cyclonic growth and deepening depend upon their distribution within the cyclone (Nuss, 1989). Reed and Albright (1986) found that large positive surface heat fluxes to the northeast of a cyclone enhanced cyclogenesis. While the distribution of surface heat flux relative to the cyclone was similar in the three case studies, larger values of surface heat flux were present to the north and northeast in the moderate and intense cases. Additionally, heating of the surface layer in the vicinity of the surface low and frontal zone was more sustained in the moderate and intense cyclones.

Nuss and Kamikawa (1990) found that weak tropospheric stability in the vicinity of sustained positive heat fluxes around a oceanic low combined with strong baroclinic forcing aloft to initiate rapid cyclogenesis.

To examine boundary layer and mid-tropospheric stability, frontal structure and vertical motion associated with the upper-level and planetary boundary layer (PBL) dynamics, cross sections of potential temperature, equivelent potential temperature, the ageostrophic vertical circulation and the isotachs of the wind perpendicular to the cross section were constructed for the three individual cases. Vertical velocity was computed kinematically and corrected using a method from O'Brien (1970) . The location of the cross sections were east of the cyclones through the frontal zone at 12-h prior to the mid-point of maxixmum deepening and at the mid-point of maximum deepening. Positions of the cross sections for the three cases are shown in Figs. (20, 21 and 22).

A. WEAK CASE

The transverse circulations associated with the entrance and exit regions of upper-level jet streaks play an important role in surface cyclogenesis and deepening. As shown in Fig. (6), at time 1200Z 18 February, the weak cyclone is positioned ahead a 60 m/s jet to the south in an area of weak divergence aloft but is less favorably positioned beneath a 60 m/s jet streak to the north in an area of probable convergence aloft. The 1200Z 18 February cross section constructed east of the cyclone center through the warm frontal region, at the midpoint of maximum deepening, reveals that the maxixmum vertical motion is centered between the two upper-level jets

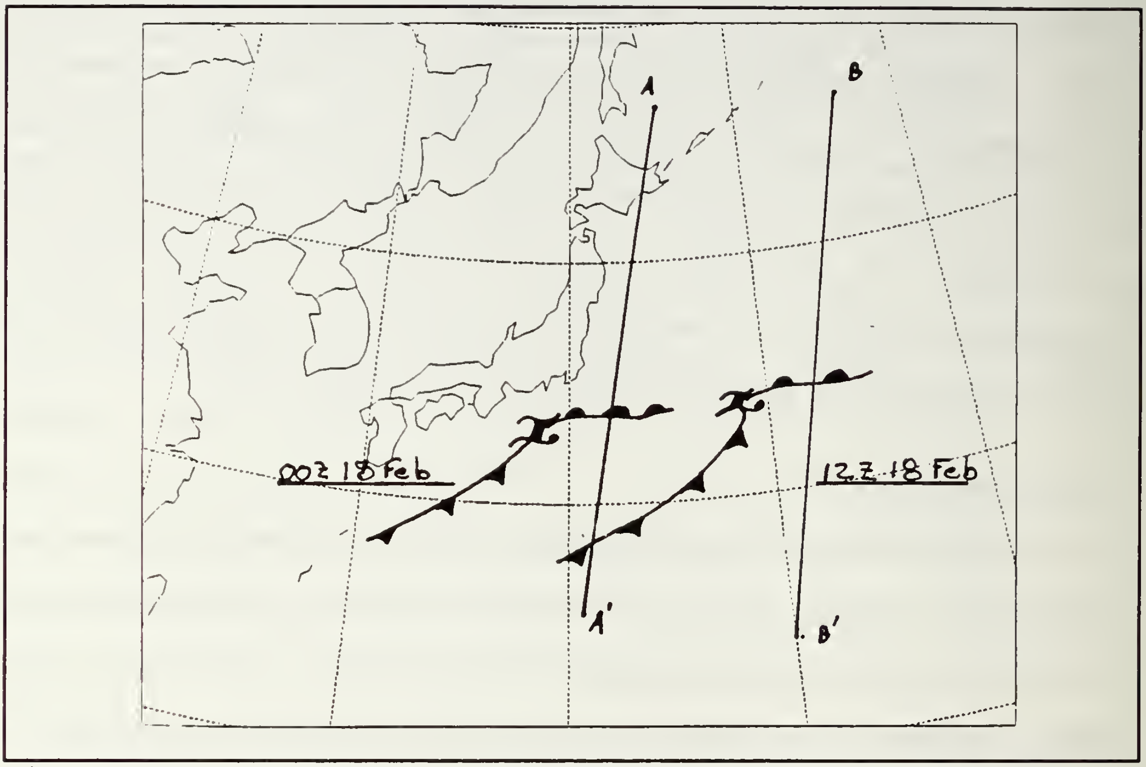

Figure 20. Location of cross sections for 0000Z 18 February and 1200Z 18 February 1987.

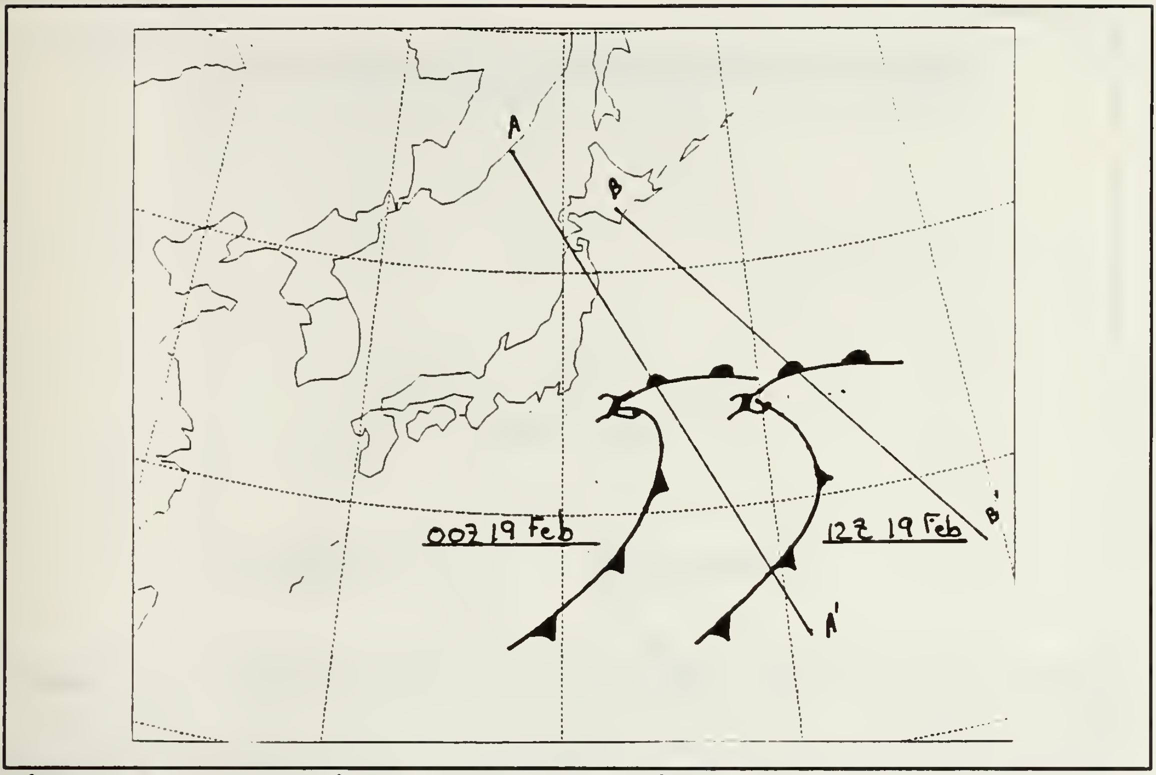

Figure 21. Location of cross sections for 0000Z 19 February and 1200Z 19 February 1986.

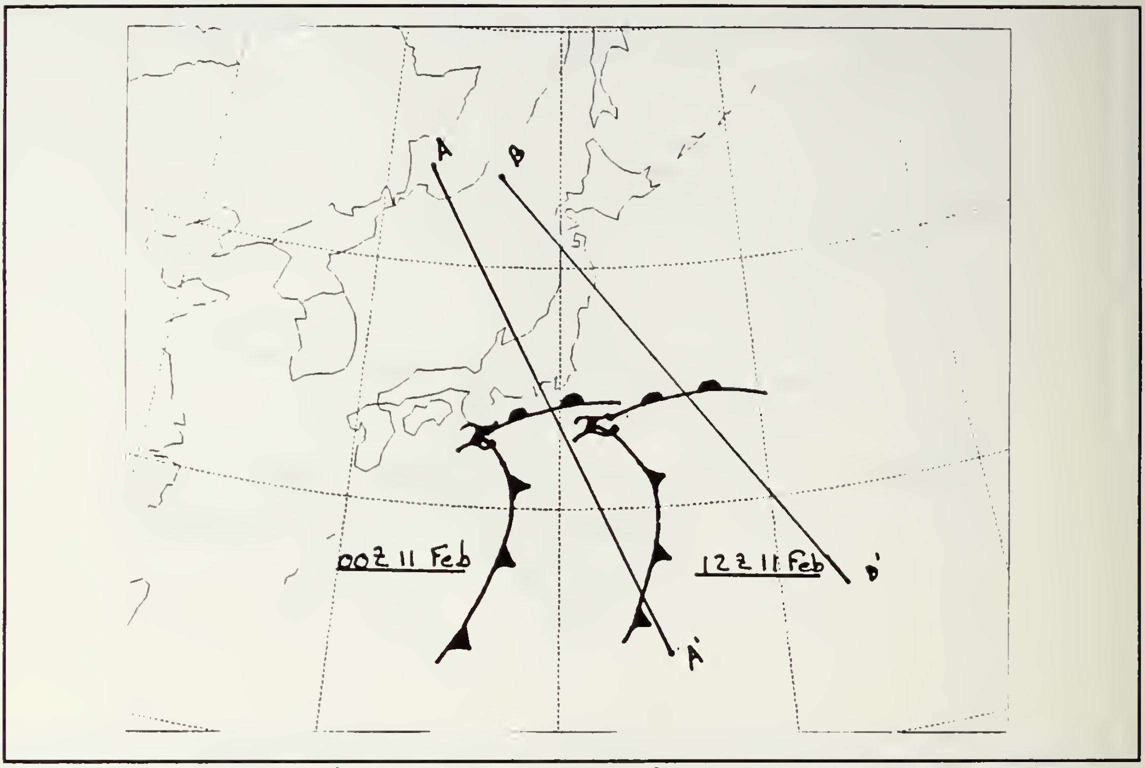

Figure 22. Location of cross sections for 0000Z 11 February and 1200Z 11 February 1986.

over the frontal region (Fig. 23). Both the direct circulation associated with the entrance region of the downstream jet and the indirect circulation associated with upstream jet are evident. Uccellini and Kocin (1987) found that the interaction between these two circulations produced strong vertical motion in cyclones off the East Coast of the United States. A

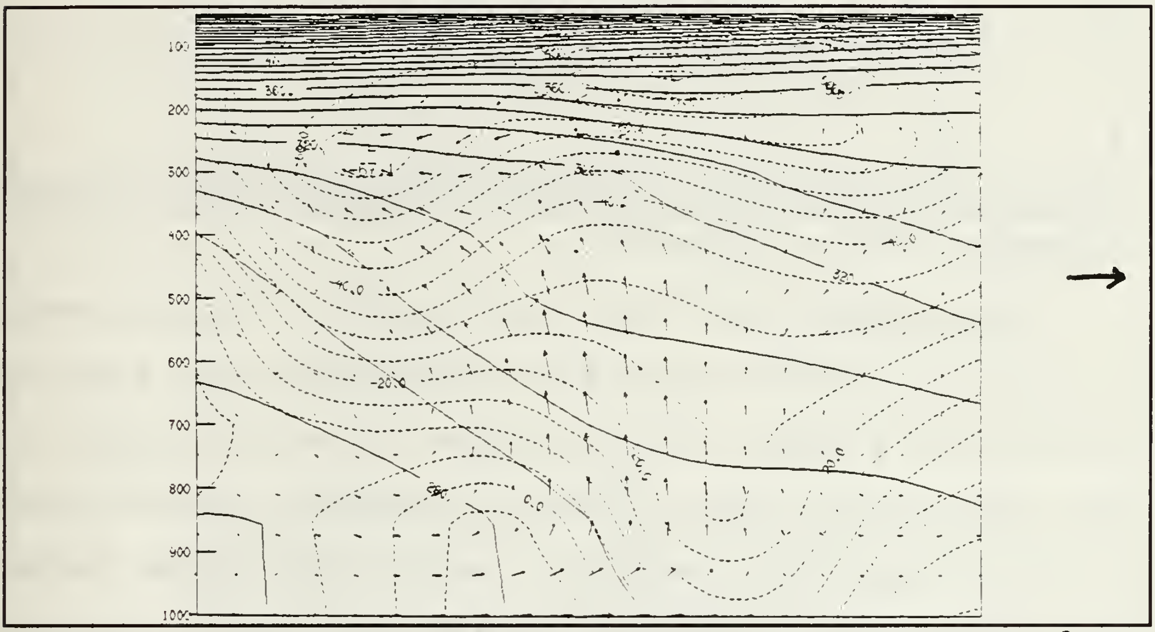

Figure 23. 1200Z UTC 18 February 1986 Cross section of θ and isotachs: θ in K (solid) and isotachs in m/s (dashed). Arrows are ageostrophic wind with maximum vector to right of figure. Location of cross section shown in Fig. 20.

comparison of Fig. 23 with a cross section constructed east of the cyclone at time 0000Z 18 February, the start of the deepening phase (Fig. 24), reveals that the updraft region has been significantly enhanced by its position between the two upper-level jets.

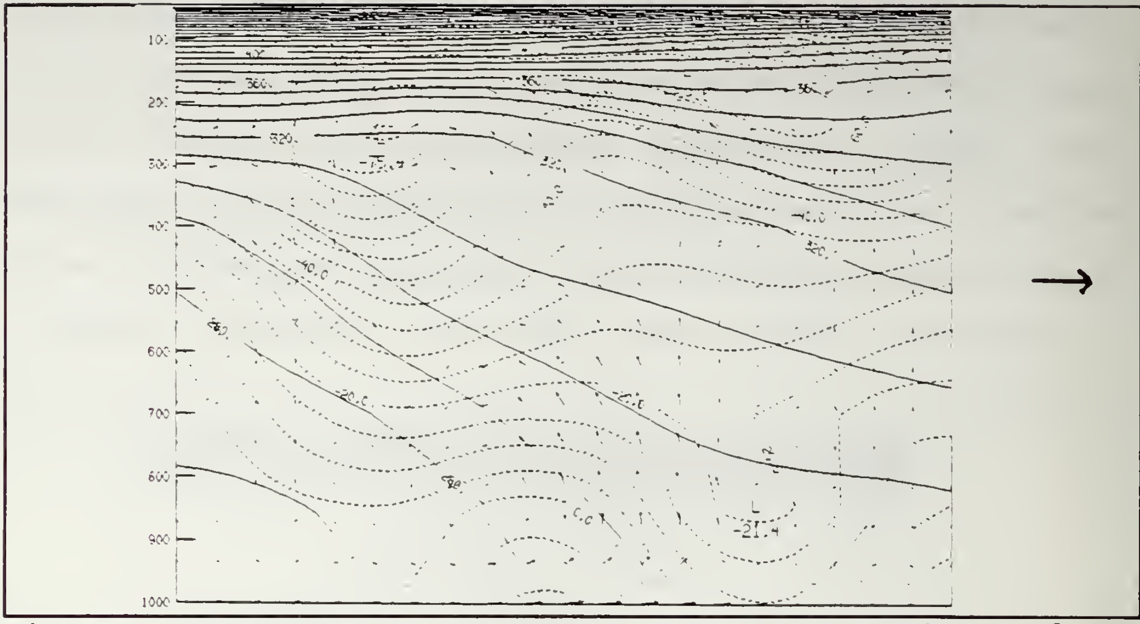

Figure 24. 0000Z UTC 18 February 1986 Cross section of θ and isotachs: Same as Figure 23.

The boundary layer structure at 1200Z 18 February reveals a well-mixed layer north of the frontal region with a top near 850-mb, and a stably stratified layer to the south (Fig. 23). This was not the case at 0000Z 18 February when the region north of the frontal zone was weakly stable. This suggests increased surface heating to the north over the 12-h period as shown in the horizontal analysis (Fig. 7) in the last chapter. In model simulations of an idealized maritime cyclone, this pattern of a destabilized boundary layer by positive heat fluxes north of the frontal region and a stably stratified boundary layer to the south was cited by Nuss (1989) as potentially significant in enhancing vertical motion, through enhanced frictional convergenge in the PBL.

A potential reason that this weak cyclone did not significantly deepen can be shown by a closer examination of the boundary layer stability in Fig. 25. At time 1200Z 18 February, the θ_e cross section through the same region as the θ cross section for the same time, reveals a potentially unstable boundary layer up to 850-mb within the frontal region

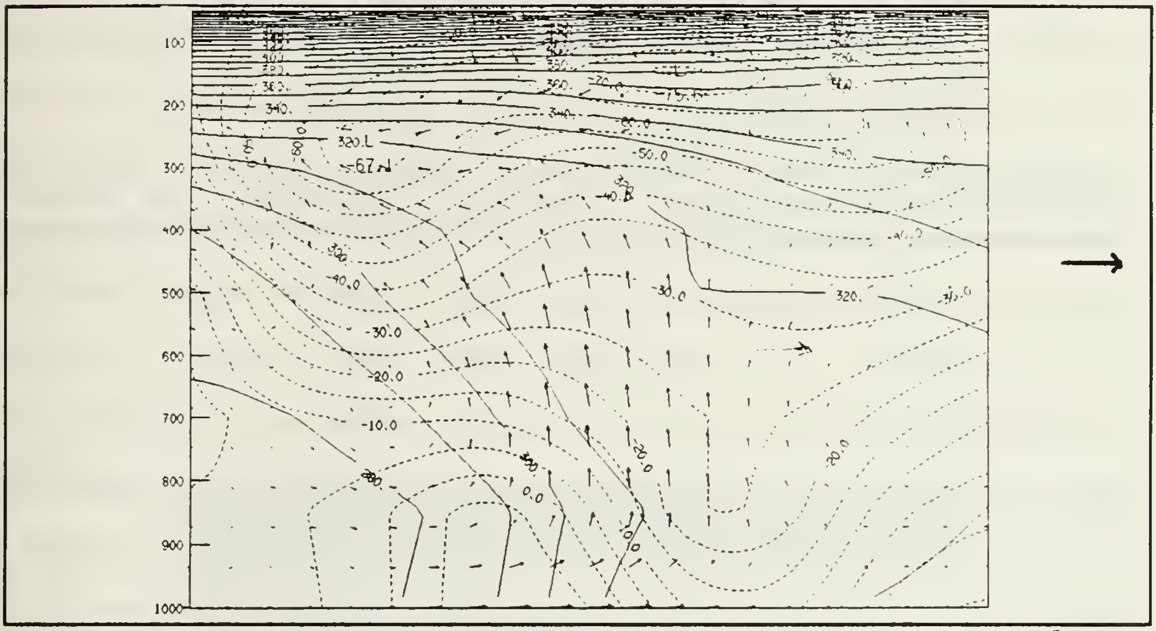

Figure 25. 1200Z UTC 18 February 1987 Cross section of θ_e and isotachs: θ_e in K (dashed) and isotachs in m/s (dashed). Same as Fig. 23.

extending northward and capped by a stable layer above 850-mb. Three requirements for coupling between the upper-level forcing and boundary layer forcing are weak stability through the mid-troposphere, strong forcing aloft resulting in a narrow updraft region and sustained positive surface fluxes. The combination of weak upper-level forcing and strong mid-tropospheric stability has combined to limit the effects of

the surface fluxes to the surface layer below 850-mb and their contribution to the development of this weak cyclone was minimal.

B. MODERATE CASE

The position of the moderate cyclone at time 1200Z 19 February in close proximity to the left exit region of a 80 m/s jet streak and in a region of positive voticity advection ahead of the 500-mb trough suggest this system developed under more organized conditions aloft than that observed in the weak system. The 1200Z 19 February cross section (Fig. 26) constructed east of the cyclone through the warm frontal zone shows a broader region of ascent with greater magnitude than that observed in the weak case. The strong indirect circulation associated with the exit region of the upper-level jet is evident and the presence, at 850-mb, of a 35 m/s LLJ south of the frontal region is consistent with the findings of Uccelinni et al. (1987) who determined this feature to be characteristic of a strong indirect circulation.

The boundary layer, at 1200Z 19 February, is weakly stable north of the frontal region and stably stratified to the south. However, destabilization of the mid-troposphere to the south of the frontal region above 700-mb (Fig. 26) has evidently occurred as the cross section reveals a wide seperation of the θ lines not present 12-h earlier(Fig. 27). This indicates possible latent heat release (LHR) is occuring

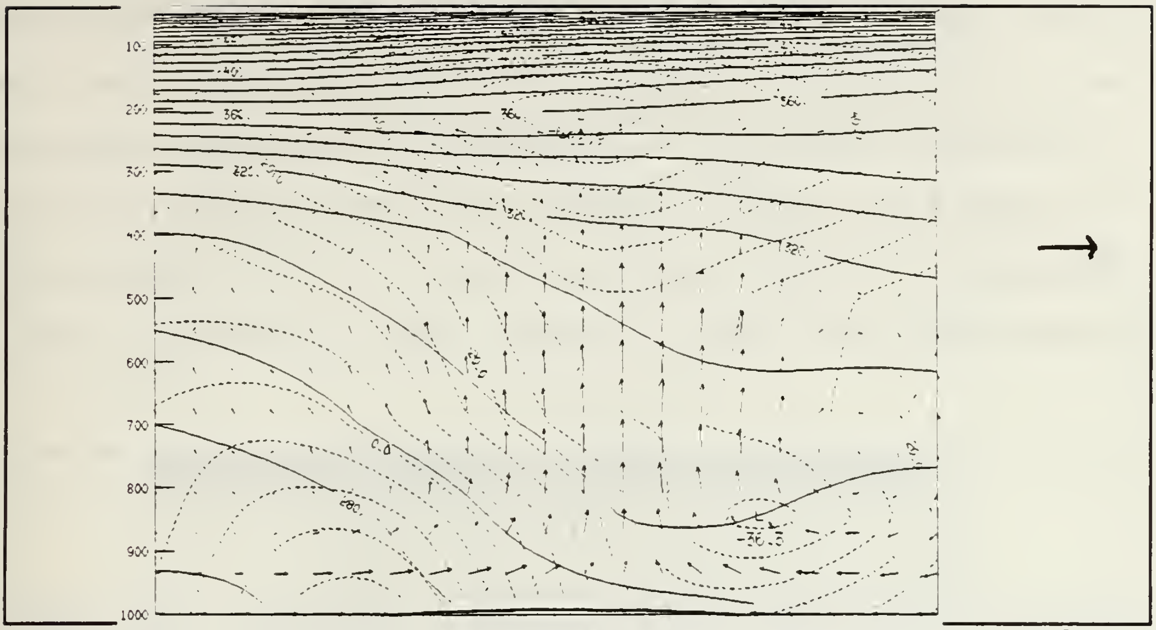

Figure 26. 1200Z UTC 19 February 1986 Cross section of θ and isotachs: Same as Fig. 23. Location of cross section shown in Fig. 21.

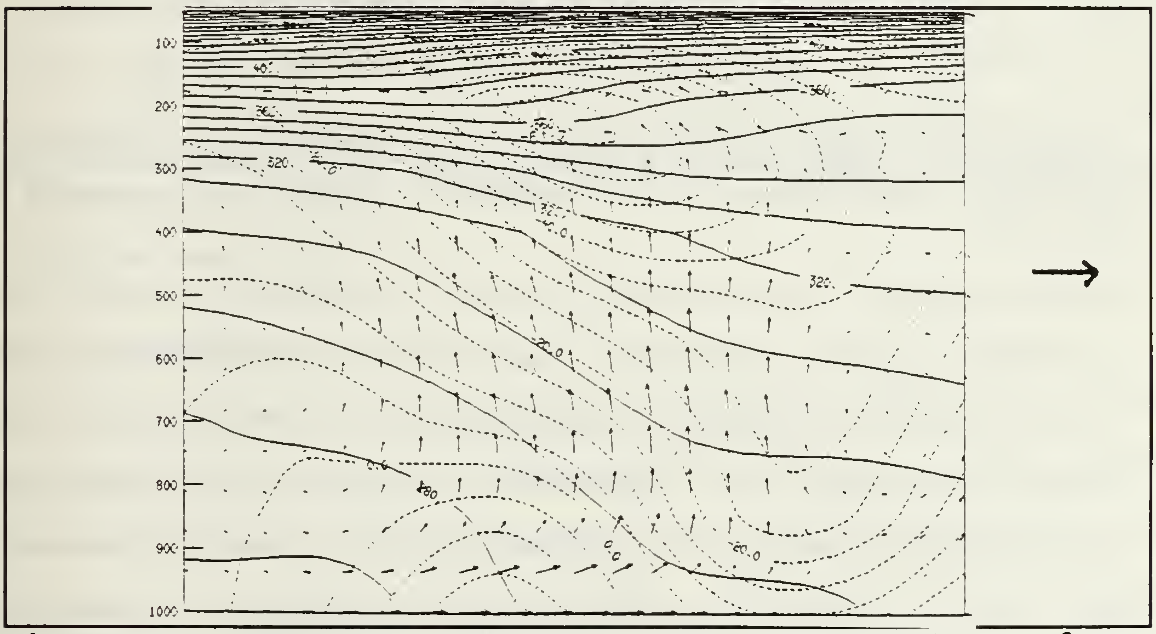

Figure 27. 0000Z UTC 19 February 1986 Cross section of θ and isotachs: Same as Fig. 26.

above 700-mb. Fig. (28) is a cross section of θ_e constructed east of the cyclone through the frontal region at time 0000Z 19 February, 12-h prior to the mid-point of maximum deepening. It reveals an unstable boundary layer up to 850-mb extending through the frontal region northward. A cross section of θ_e constructed 12-h later, at time 1200Z 19 February, shows a

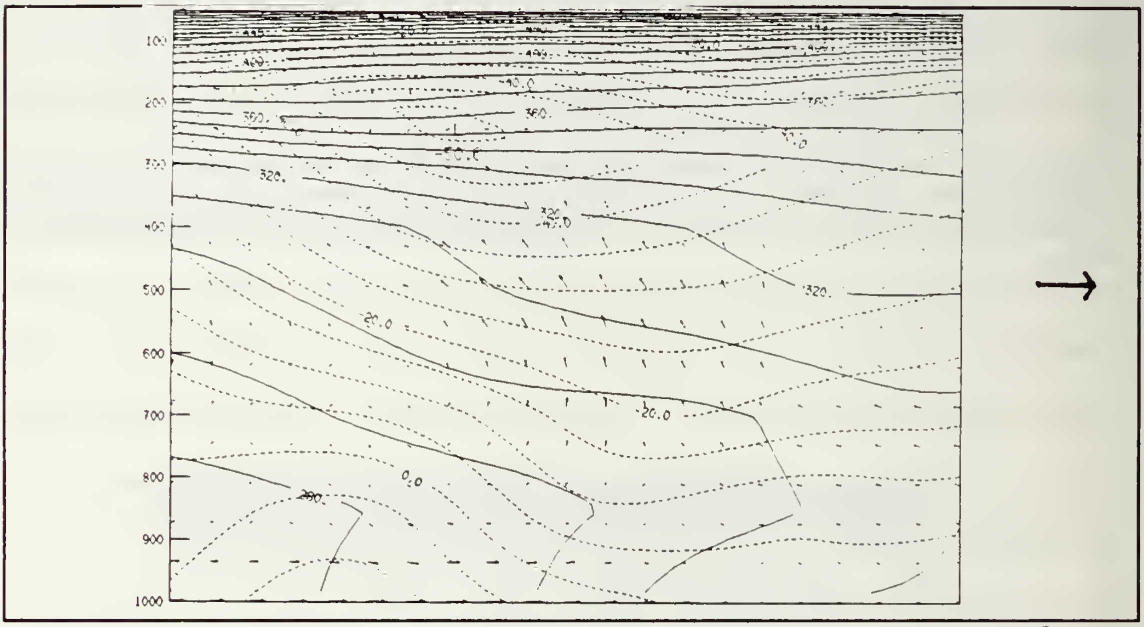

Figure 28. 0000Z UTC 19 February 1986 Cross section of θ_e and isotachs: Same as Fig. 25. Location of cross section shown in Fig. 21.

stabilization of the boundary layer through the frontal zone with near neutral conditions above 850-mb in the frontal zone and potentially unstable conditions above 850-mb south of the frontal zone (Fig. 29). Apparently, over the 12-h period, the instability present in the boundary layer at 0000Z 19 February has been released and transported vertically to the mid-troposhere. The result is the release of latent heat which was

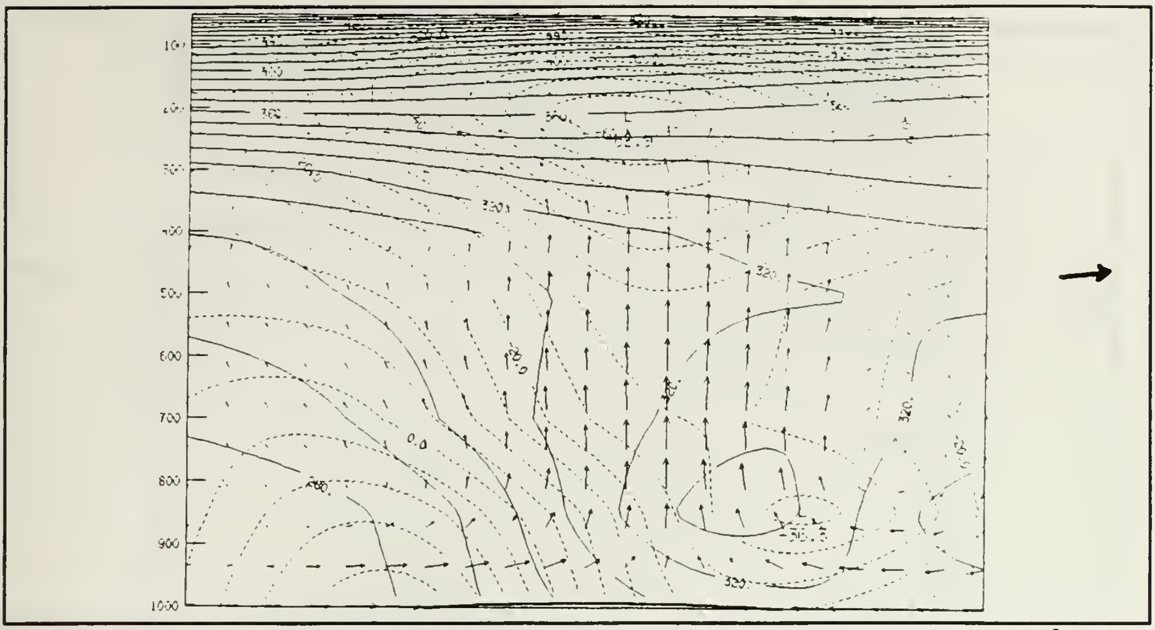

Figure 29. 1200Z UTC 19 February 1986 Cross section of θ_e and isotachs: Same as Fig. 28.

suggested by the stability changes in the potential temperature cross section at 1200Z 19 February. This is consistent with the results of Chen and Dell'Osso (1987) who found that the primary role of surface fluxes was to enhance the effects of LHR aloft. The mechanism to transport the instablity aloft is the strong forcing at 300-mb and the decrease in stability through the mid-troposphere as discussed in the weak case.

C. INTENSE CASE

It was noted in the synoptic discussion that the intense cyclone was located in a region of strong divergence aloft associated with the 80 m/s subtropical jet streak at the mid-point of maximum deepening. Fig. (30) is a cross section

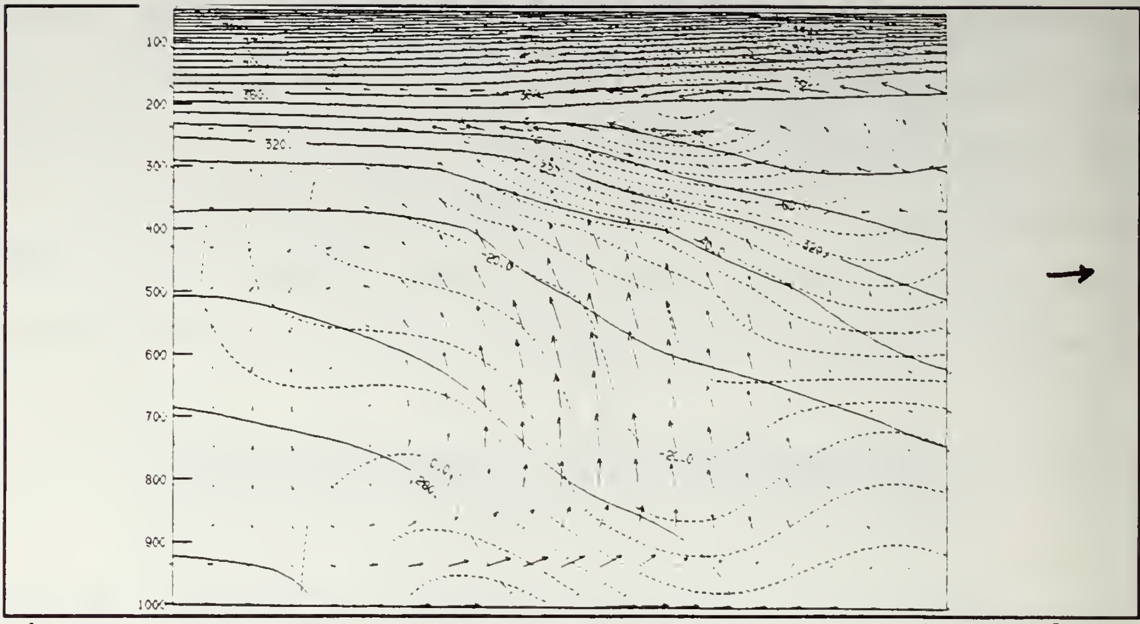

Figure 30. 1200Z UTC 11 February 1986 Cross section of θ and isotachs: Same as Fig. 23. Location of cross section shown in Fig. 22.

constructed east of the cyclone through the 80 m/s subtropical jet streak and shows the narrow and intense updraft region associated with the storm at time 1200Z 11 February. The vertical motion is confined to a narrow region located over the surface cyclone and frontal region. Also evident is the direct circulation associated with the entrance region of the upper-level jet streak. This pattern suggests strong forcing aloft. A cross section through the frontal zone at time 0000Z 11 February revealed a very weak updraft region even though the relative strengths of the jet streaks are the same (Fig. 31). This suggests that the favorable positioning of the low, at 1200Z 11 February, in a region of strong divergence aloft, has enhanced the vertical motion over the cyclone as cited by Wash et al. (1988).

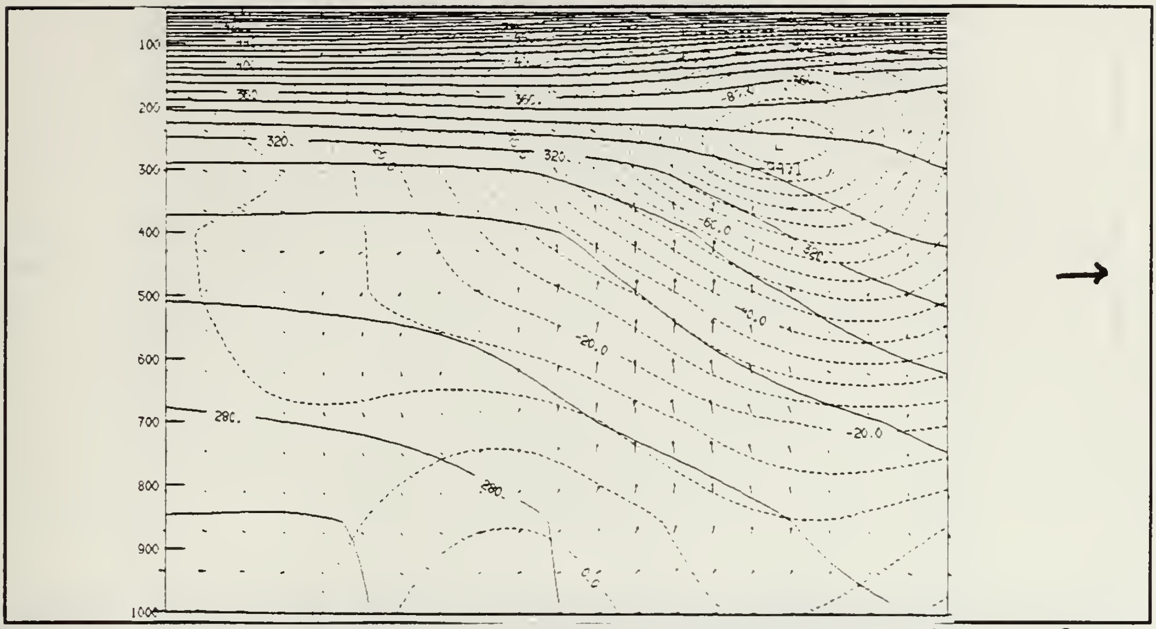

Figure 31. 0000Z UTC 11 February 1986 Cross section of θ and isotachs: Same as Fig. 30.

The boundary layer structure for this intense case is similar to that observed in the moderate case and suggests that similar forcing is taking place in the PBL. At 0000Z 11 February, the cross section of θ located east of the cyclone through the frontal region reveals a near neutral boundary layer up to 850-mb north of the frontal zone with stably stratified conditions in the frontal zone and to the south (Fig. 31). A cross section of θ_e taken at 0000Z 11 February through the same region as the θ cross section shows a potentially unstable boundary layer north of the frontal zone extending southward into the frontal region (Fig. 32). As observed in the moderate case, this represents a potentially explosive environment for rapid deepening as cited by Nuss and Kamikawa (1990). By 1200Z 11 February, a θ cross section

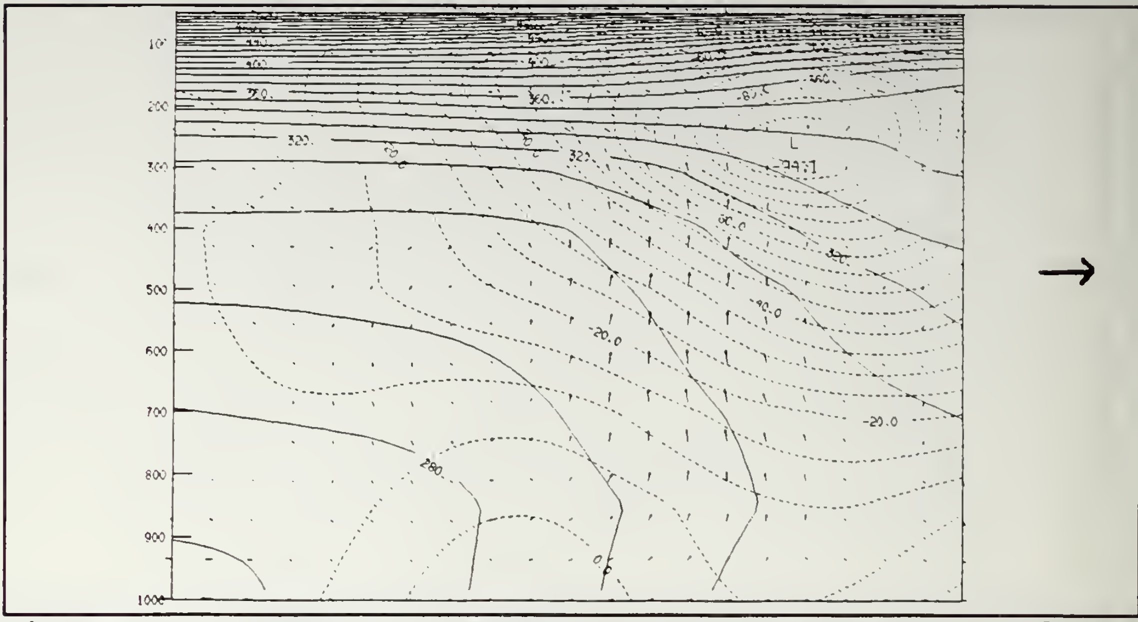

Figure 32. 0000Z UTC 11 February 1986 Cross section of θ_e and isotachs: Same as Fig 25. Location of cross section shown in Fig. 22.

constructed east of the cyclone through the frontal zone reveals that stabilization of the boundary layer to the north extending southward through the frontal zone and into the warm frontal region has occurred (Fig. 30). As was observed in the moderate case, there is evidence of destabilization in the mid-troposhere indicating LHR above 700-mb. This pattern, as was noted in the moderate case, suggests the vertical transport aloft of the low level instability present at 0000Z 11 February to the mid-troposhere. Unlike the moderate case where a cross section of θ_e showed stable conditions existed through the boundary layer at the mid-point of maximum deepening, a cross section of θ_e taken east of the cyclone through the frontal zone, at time 1200Z 11 February, shows near neutral conditions north of the frontal zone (Fig 33).

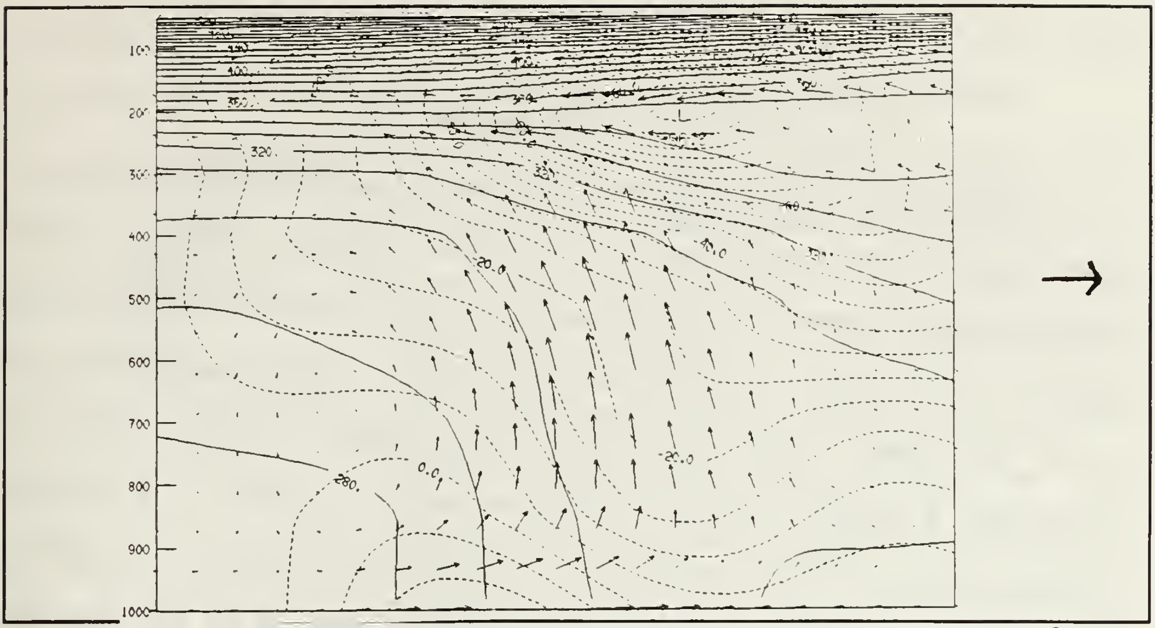

Figure 33. 1200Z UTC 11 February 1986 Cross section of θ_e and isotachs: Same as Fig 32.

The neutral conditions north of the frontal region and the strong forcing aloft suggest a more suitable enviroment for the coupling between the strong upper-level forcing and boundary layer forcing in this cyclone than that observed in the moderate cyclone. Although the surface heat flux was greater north of cyclone in the moderate case as discussed in the case analysis the transport of the heat and moisture flux aloft north of the intense cyclone was greater and indicates that the role of these surfaces fluxes in contributing to the rapid deepening of this cyclone is potentially more significant than that seen in the moderate case.

V. DISCUSSION

Previous climatological studies have found the region to the south and southwest of Japan highly susceptible to cyclogenesis during the winter months. Hanson and Long (1985) determined that a wintertime maximum in cyclogenesis occurs over the East China Sea with a secondary maximum occurring over the Kuroshio current. Gyakum et al. (1989) in a study of cold season cyclone activity in the North Pacific found that 90% of the cyclones passing through the region of the Kuroshio deepen.

Of the twenty seven cyclones examined in this study nineteen developed over the East China Sea and surrounding regions. Twenty-two showed a 24-h maximum deepening phase once they had tracked over the Kuroshio.

Upper-level forcing has been cited in numerous studies as a key forcing mechanism in cyclonic development and explosive deepening. Uccellini and Kocin (1987) found that the transverse circulations associated with the entrance and exit region of uper-level jet streaks were important in producing divergence aloft over a surface cyclone. Reed and Albright (1986) determined that rapid deepening occurred in response to the jet stream. Wash et al. (1988) demonstarted that the favorable position of the surface cyclone could enhance development. Results from this study agree with previous

studies and provide some distinction between weak and strong cyclones by these upper-level forcing characteristics.

Classification of the twenty-nine cyclones in this study were, in part, determined by the degree and organization of their upper-level forcing. Weak cyclones were often positioned in regions of weak vorticity advection or convergence aloft. The case study analysis of the weak cyclone demonstrated that at the mid-point of maximum deepening it is positioned in a region of probable convergence aloft. By contrast, moderate and intense cyclones were characterized by a high degree of organization aloft. These cyclones were often positioned in areas of strong positive vorticity and divergence aloft. The case analysis showed that the favorable positioning of these systems relative to the upper-level forcing significantly enhanced their development.

The role of boundary layer forcing in this study was confined to an examination of the thermal advection patterns and distribution of surface fluxes around the cyclone. It has been shown that weak flux gradients across the frontal zone was characteristic of weak cyclones. This was indicative of the weaker advection of cold air to the north and east of the cyclones in the weak systems. Moderate and intense cyclones were characterized by stronger flux gradients in this region. This pattern of strong heating within the surface layer, resulting in larger heat flux values, in the vicinity of a

cyclone has been cited by Atlas (1987) as a potential contributor to rapid development.

Nuss (1989) suggested that the distribution of surfaces fluxes relative to the developing cyclone was critical to explosive development. Reed and Albright (1986) found that large positive values to the northeast of a cyclone created a potentially explosive environment for rapid cyclonic growth. In the case analyses presented, the distribution of surfaces fluxes were similar in all three cases. Positive values of surface flux were present to the north and east of the weak, moderate and intense cyclones throughout their life cycle. Uccellini et al. (1989) and Chen and Dell'Osso (1987) showed that the contribution of surface fluxes were important only so far as they contributed to LHR in the mid-troposhere. Analysis of the boundary layer for the three case study cyclones showed that the surface fluxes were confined to the PBL in the weak case by the absence of sufficient forcing aloft to move their energy vertically. The strong forcing aloft in the moderate and intense case provided the mechanism by which the contribution from the surface fluxes could be tapped. That the moderate cyclone did not experience the explosive development seen in the intense system is probably the result of a slightly more stable boundary layer during the deepening period.

VI. CONCLUSIONS AND RECOMMENDATIONS

Upper-level and boundary layer forcing can be a useful tool in charaterizing the development pattern of Western Pacific cyclones. Weak cyclones exhibited a lack of organized forcing at 500-mb and 300-mb and a thermal advection pattern that resulted in low positive values of surfaces fluxes across the frontal region. These systems developed slowly showing a central pressure fall of 16-mb or less during a 24-h maximum deepening period. Moderate and intense cyclones were characterized by strong, organized forcing at 500-mb and 300-mb and a thermal advection pattern that resulted in large values of surface fluxes across the frontal zone. As was demonstrated in the case studies, this combination of strong forcing aloft and significant heating in the vicinity of the low was necessary for coupling. These moderate and intense cyclones developed quickly showing central pressure falls of greater than 20-mb and 24-mb respectively, in a 24-h maximum deepening period.

While the upper-level forcing and surface heating pattern of twenty four of the twenty seven identified cylones was limited to a qualitative analysis of observed patterns, a detailed analysis of the coupling between upper-level forcing and forcing in the boundary layer was conducted on the three individual case cyclones. The results they provided give

insight into the possible coupling mechanisms at work in the other weak, moderate and intense systems. The role of upper-level and boundary layer forcing in contributing to the development of the three case study cyclones can be summarized as follows:

1. The ageostrophic circulation associated with stronger 500-mb and 300-mb forcing in the moderate and intense cases resulted in an enhanced region of vertical motion over the frontal zone. The presence of this enhanced updraft region, while certainly contributing to the deepening process of the two cyclones, provided a potentially significant vehicle for the movement of surface fluxes within the PBL to the mid-troposhere.

2. While the distribution of surfaces fluxes was similar in all three cases, only in the moderate and intense cases were large positive values of surface fluxes present north and east of cyclones during the maximum deepening phase.

3. The contribution by surface heat and moisture fluxes to the development of the weak cyclone was confined to the PBL below 850-mb by the lack of a significant mechanism to transport these fluxes vertically. Only in the moderate and intense cases was the baroclinic forcing aloft strong enough to vertically transport the heat and moisture out of the PBL to the mid-trposphere and significantly contribute to the development of the cyclone.

A. RECOMMENDATIONS

Since the classification and general characteristics of Western Pacific systems was accomplished using a data base of twenty seven cyclones, it is recommended that a larger data

base be utilized to refine the classification process and determine if other characteristics within each classification exist.

A detailed analysis of the upper-level and boundary layer forcing in the weak, moderate and intense cases was confined to only one case respectively. Further study involving multiple cases within each classification is required to determine if the forcing mechanisms observed in this study are truly characteristic of the three cyclone classifications.

It was apparent from the case analyses that the surface fluxes and upper-level forcing were significant contributors to the deepening process of the moderate and intense systems. A more quantitative approach to analysing their contribution to the deepening process is recommended. Additionally, modelling studies that vary the intensities of surface heat and moisture flux during the maximum deepening phase would help to further explain their contribution to the deepening process.

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